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REPORT ON LABORATORY TEST OF THE
AERIAL PROFILING OF TERRAIN SYSTEM

by

James A. Hand

February 1983

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The Charles Stark Draper Laboratory, Inc.

Cambridge, Massachusetts 02139

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ACKNOWLEDGEMENT

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1.SCOPE

This report covers laboratory testing of the Aerial Profiling of Terrain System (APTS) from December, 1981 to completion in January, 1983.

2. INTRODUCTION

At the end of the Government Fiscal Year (GFY) 1981, Draper Laboratory completed the Phase 5 contractual effort of fabrication, assembly and test of the hardware and software elements which comprise the APTS. This work is described in Draper Report No. R-1451. A transitional test phase was then undertaken from 1 October through 15 December '81; this period being used for additional test of the APTS subsystems, and then system integration as reported in Draper Report No.R-1521. On 16 December 1981 the Phase 6 contractual effort began with the formal start of system integration testing, and then functional and performance testing. At the completion of this work, described herein, the APTS was dismantled and inspected by the Draper Reliability and Quality Assurance Department in preparation for shipment to Hanscom Field to begin the shakedown and performance evaluation flight testing. The R&QA inspection results are included in this report. The flight testing phase is scheduled for completion by 15 June, 1983, whereupon an operational phase is planned with various applications of the APTS.

All of the work described in the sections which follow was performed in two locations at the Draper Laboratory. Functional checkout of the Laser Tracker, Laser Profiler and Video Subsystem was conducted primarily in the Fifth Floor Lab. and then completed in the System Lab. on the first floor, this being the location of the major APTS test effort. Parenthetically, during the report period the Video Subsystem was successfully subjected to a series of flight tests as separately described by Draper Memo No. APTS-T-330. Section 3 of this report presents an overview of the laboratory-level system test program. Then, Section 4 contains a test log summary with some augmenting text. Section 5 describes some of the salient results. Finally, Section 6 outlines the engineering and the Acceptance Test procedures and the results of these tests; i.e., the final system testing which assured that the APTS performance is adequate for moving forward to field and then flight test.

3. OVERVIEW OF THE LABORATORY LEVEL SYSTEM TESTING

3.1 ORGANIZATION OF PROGRAM

Figure 3-1 illustrates the general organization of the test program in the laboratory and the performance evaluation flight program which will follow. A series of tests were conducted, first to show that the subsystems had been properly integrated, then to demonstrate proper functions, then to verify performance from an engineering viewpoint, and finally to verify performance acceptable for fielding the system. Accordingly, these test sequences are so labeled in the figure.

As noted in the figure, the exact sequence of testing was determined at the time of test. This flexibility was needed for the developmental effort. Note 2 refers to the fact that the IMU was first tested in the normal operating orientation and then in an inverted orientation allowing for increased retro viewing and rotary table tipping which permitted calibration of the Tracker-to-IMU gimbal attitude. In the final engineering acceptance testing the upright orientation, identical to the flight orientation, was employed.

Notes 3 and 4 at the bottom of the figure refer to the planned installation of flight gyros after several functional checks of the C&A test procedure. As the program evolved, the flight gyros were actually used for both functional and performance testing. Finally, as mentioned by Note 5, the Profiler/Tracker Boresight Test will be conducted in the field. This approach was selected because there is not enough range in the laboratory to conduct the alignment.

One characteristic of the test program not indicated by the chart is that the identified functional tests were conducted many times during the course of the effort. This is because many of the moding and control functions are prerequisite to operating the system for a given performance test.

Figure 3-1. APTS INTEGRATION AND TEST FLOW

SYSTEM TEST LABORATORY				AIRCRAFT
		Performance Tests		
System Integration	Functional Tests	Engineering	Acceptance	Performance Evaluation Flight Test

• IMU/Tracker Mounting Base
• IMU/Tracker/Rotary Table
• AC Power
• DC Power
	• Moding & Control & Displays
	  IMU
	  Tracker
	  Profiler
	• LT Ranging & Tracking
	• Functional ADC Verification
	• Functional LCA Verification
	• EEU/Lab Test Software
		• Laboratory C&A(2)(3)
		• Tracker Calibration & Alignment
		• Post-Processing
		• Diagnostic & Process Sensitivity Calibration
		• In-Flight Software Package
			• Moding & Control
			• Three Back-to Back Laboratory C&As(4)(A)
			• Post-Processing of Lab Data
			• Navigation Base Fit Check
			• In-Flight Software Package
			• Post-Flight Calibration
				• Aircraft Integration Tests
				  • Power Transfers
				  • Cooling
				  • Mechanical Alignment(5)
				• Taxi Test
				• Shakedown Flights
				• Post-Flight Lab Testing (Return to A)
				• Post-Flight Processing

Notes: (1) The exact sequence of test will be determined at test time.

(2) First upright then inverted IMU/tracker tests.

(3,4) Repeated calibration and alignment before and after flight gyro installation.

(5) Includes profiler/tracker boresight alignment.

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3.2 IMPROVED PERFORMANCE TEST APPROACH

The referenced figure illustrates the Lab. Test Program as originally planned. The initial planning called for three back-to-back C&A tests to demonstrate the repeatability of the system, as shown in the acceptance column. Such tests would require approximately 53 hours per C&A. The acceptance procedure was then improved to require only a single C&A test and then 2.5 hours of IMU drift test and 2.5 hours of Tracker-aided navigation. Also, the C&A test, itself, was improved to require only 44 hours elapsed time. Finally, the development testing showed that a simpler 'azimuth slew' and then earth-fixed hold test would suffice to replace the C&A, thereby reducing the elapsed test time to approx. 24+2.5+2.5=29 hours. The importance of these improvements, aside from the reduction in acceptance test time, lies in the fact that they suggest that time required for system calibration and alignment in field test may be typically an overnight abbreviated C&A with the more extensive 44-hour C&A test performed only occasionly. Of course these improvements remain to prove themselves over the period of several field tests and additional design work on the C&A trajectories to be employed.

3.3 ENGINEERING TESTS

3.3.1 FUNCTIONAL EVALUATIONS

Many functional tests were conducted during the course of the program, particularly with regard to checking the IMU, Tracker and Flight Computer. Examples of the IMU checks inlude evaluation of thermal control of the stable member as a function of stable member attitude and orientation with respect to the outer case, thermal control of the inertial instruments, servo control stability as a function of stable member attitude and functional checks of the gyro flotation error within each instrument (i.e., error in flotation as a function of temperature). Typically, these functional tests were conducted in parallel with performance tests in that the telemetry data from the IMU permits continuous monitoring of data during performance evaluation. Examples of Tracker engineering tests include long-range acquisition and static tracking of a retro (at the max. range of one mile), a check of range and angle tracking stability vs time and temperature variation and tracking stability vs time-of day. Examples of the Computer functional tests include memory diagnostics, power up-down sequencing, continuous monitoring of mode, hourly checks of alarm channel status, printouts of

initial and terminal conditions employed in test and continous parity and Direct Memory Access monitoring. Except for the memory diagnostics and power sequencing, these checks were performed in parallel with the performance tests. Data from all such functional testing of APTS are available for review --- they are not reproduced herein for lack of space.

3.3.2 DIAGNOSTIC PERFORMANCE TESTING

In overview, the sequence of events involving performance testing was typically to conduct an IMU C&A test, then evaluate the results for systematic (unmodeled) errors and then adjust the Kalman filter preparatory to the next test. Often, as shown by the test log summary, later reproduced, diagnostic tests of the IMU were conducted between C&A,s. The particular diagnostic trajectory of the IMU stable member which proved so valuable was the so-called azimuth slew, or carousel; this being characterized by a revolution in local azimuth whereby the gravity change on the instruments was nil. This specific trajectory permits calibration of 21 of the 57 IMU states of interest and results in alignment of the stable member relative to azimuth and level. Also, at the conclusion of this trajectory, simply holding the stable member still in earth space under C&A control proved very valuable for stabilizing final estimation and control.

Engineering evaluation of a C&A or carousel test is a rather detailed procedure as shown by Table 3-1. The work required after such an evaluation involves either trimming the Kalman Filter, investigating apparent instrument anomalies, performing a repeatability test or switching to a different trajectory or torquing rate to disclose error sources more readily. Essentially, the procedure is to build a data base of performance results that demonstrates repeatability, stability and the abscence of unmodeled errors which are characterized by systematic disturbances in the test data.

During the Lab. Test Program, there were problems evident in each of the catagories just listed and all were addressed and solved prior to fielding the APTS. For instance, apparent instrument instablities were investigated, resulting in the removal of a suspected poor gyro, then shown to be caused by torquing the inertial platform stable member at an excessive rate. Once this problem was solved with a procedural change, the performance improved substantially such that small residual errors then became detectable. There were systematic characteristics of these errors which suggested either magnetic or thermal sensitivity of accelerometer performance. A series of carousel tests with

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Table 3-1. <u>ENGINEERING EVALUATION OF C&A TEST</u>

- COMPARE INSTRUMENT-LEVEL TEST RESULTS VS. C&A STATE ESTIMATES.

- EVALUATE FUNCTIONAL DATA (TEMPERATURES, POWER, VOLTAGES) FOR STABLE PERFORMANCE.

- EVALUATE PLOTS OF DATA FOR CLOSE AGREEMENT BETWEEN INITIAL AND FINAL STATE ESTIMATES, AND FOR ABSENCE OF SYSTEMATIC TERMS.

- EVALUATE FILTER $\tilde{G}$-RESIDUALS FOR SMALL MAGNITUDE, STABILITY, AND AND ABSENCE OF SYSTEMATIC TERMS.

- EVALUATE ERROR IN MAGNITUDE OF G (I.E., RSS OF THREE ACCELEROMETER OUTPUTS SHOULD EQUAL 1 G) FOR SMALL MAGNITUDE AND ABSENCE OF SYSTEMATIC ERROR (UNMODELLED TERMS).

J. HAND
28 SEPTEMBER 1982

Table 3-1. ENGINEERING EVALUATION OF C&A TEST (CONT.)

- EVALUATE PLOTS OF PLATFORM MISALIGNMENT ANGLES ($\hat{\psi}$) TO ASSURE CONVERGENCE TOWARD ZERO AS C&A PROGRESSED.

- POST-PROCESS THE GYRO TORQUE COMMANDS AND ACCELEROMETER MEASUREMENTS VS. INITIAL AND FINAL STATE ESTIMATES. COMPARE THE REAL-TIME AND THE POST-PROCESSED C&A RESULTS FOR CLOSE AGREEMENT.

- COMPARE END-POINTS OF MULTIPLE C&A TESTS FOR LONG-TERM STABILITY AND FOR TRENDS WHERE EXPECTED.

- COMPARE IMU C&A PERFORMANCE WITH PREVIOUS EXPERIENCE FROM OTHER LAB AND INDUSTRY PROJECTS.

- CONDUCT A TEST AFTER THE END OF A C&A USING "FROZEN" TORQUE WORDS AND OBSERVING SMALL DRIFT MAGNITUDE AND SMALL ERROR IN MEASURED MAGNITUDE OF G.

thermal control configuration alterations then demonstrated
the thermal nature of such disturbances. Improvement in the
thermal control of the IMU then permitted better estimation
and control during the C&A testing.

3.4 STATUS OF LAB. TEST PROGRAM

Functional, performance and quality evaluation of the APTS,
including hardware and software, indicated that the system
is ready for further test in the field. Specific indicators
of this status are the reliability of function demonstrated,
stable/repeata ble state estimation and IMU control, low
residual drift and accurate inplace navigation. Addi-
tionally, the Tracker demonstrated stable/repeatable ranging
and angular tracking within the required nominal temperature
limits. Also, the Profiler function and performance were
demonstrated in accordance with the ranging requirement of
600 meters. The Video Subsystem was demonstrated by flight
test. The Computer and peripheral equipment functioned as
required to support the sensor subsystems and control the
APTS.

4. TEST LOG SUMMARY

4.1 GENERAL

The tables which follow summarize the lab. testing to date. These tables, (4-1 through 4-5) list the test number, the short title and notes which describe the test and results. There are slight variations in the table format in that the originally prepared versions which were presented at the program status meetings are reproduced here. Also, the last set of tests from 19 November forward are grouped by Heading test (i.e., carousel) or C&A test as these were the last performance tests conducted and analyzed.

Imbedded within the test number are the test type, year, month, day and recording tape identification, employing the format shown below:

Test Code; last number of year (1982 or 1983); hex. number of month; day number; tape number.

The Test Codes are:

    C - Calibration and Alignment
    H - Heading; i.e., carousel in azimuth
    F - Flight navigation
    T - Tracker test
    G - Gyro diagnostic
    A - Accelerometer diagnostic
    R - Resolver diagnostic
    D - Diagnostic of Computer software
    Q - Software debugging
    X - Software debugging variation

Note that all codes are not used in the log summary, however they are retrievable from the recorded data base at Draper Laboratory.

Various identifiers of acceptability are employed in the log. "O.K."and "N.G.".are self-explanatory, "A" and "NA" are acceptable and not acceptable, based upon comparison of results with system-level requirements. Note that the test log summary begins with March 12 1982, this being the start

of the performance testing in calibration and alignment of the IMU. The log summary is presented in reverse chronological order and grouped into tables in the order presented to the USGS during the periodic progress reviews.

Table 4-1.

APTS TEST LOG SUMMARY (11/9/82 - 1/17/83)

Test No.	Title	Notes
C2B191, C2B241, C2B261, C2C051	IMU C&A	Four two-day C&A tests, IMU upright. State estimates & filter residuals showed significant trajectory-dependent deviations from the model. Unmodeled errors in accelerometers & gyros. Confirmed by post processing. Results indicate random walk in platform attitude. Error correlated with platform attitude. Estimation of g- & g-squared terms two to four times higher than permitted by mission requirements. Total budget used by g-related terms. By carousel test disturbance was isolated. See heading tests. Functional: A, Performance: NA
H2B291, H2C091, H2C101, H2C111, H2C141, H2C201, H2C231, H31041, H31071	Carousels	Test excites 21 of 57 states. Results show nonrepeatable platform wobble. Also, accel. show nonrepeatable wobble. First error not significant wrt flight; second error is important long hold segment helps negate 2-hour transients in data. Results indicate that the constant speed fan control is OK for carousels & possibly for flight; not for C&A. Closed-loop thermal control required. Data during H31071 shows that accel. performance & temp. are correlated. Function: A, Performance: NA

TABLE 4-1.

APTS TEST LOG SUMMARY (11/9/82 - 1/17/83) (CONTINUED)

TEST NO.	TITLE	NOTES
H31121, H31131		THERMAL CONTROL THERMISTOR MOUNTED TO STRUCTURE INSTEAD OF IN-AIR MEASUREMENT. CONTROL IMPROVED BY FACTOR OF FIVE. PERFORMANCE IMPROVED TWO TO ONE. FUNCTION: A, PERFORMANCE: A

TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 – 11/9/82)

Test No.	Title	Notes*
A28031 A28032	Accelerometer Calibrations	Check accelerometer bias, scale factor, and coning parameters. Test: A, Performance: A
C27261	IMU C&A	Upright C&A – filter adjustment test. Computer stopped at approximately 16 h elapsed time. Possible tape drive problem. Test: NA, Performance: Functional: A
C27291	IMU C&A	Upright C&A – filter adjustment test. Test: A, Performance: Functional: A
C28041	IMU C&A	Upright C&A – filter adjustment test. Test: A, Performance: Functional: A
R28021, R28161	Resolver Harmonics	Test IMU resolver harmonics at opposite orientations exercised in C&A. Provides calibration for resolver data compensation. Test: A, Performance: A

* A = Acceptable, NA = Not Acceptable

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TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 – 11/9/82) (CONTINUED)

Test No.	Title	Notes
C28131	IMU C&A	Upright C&A. Best real–time C&A with 1–minute filter. Error in magnitude of g approximately 2.0, peak. Same parameter using 5–minute filter should be at least $1/\sqrt{5}$ "quieter". Test: A, Functional: A.
T28271	Tracker Calibration	Test included section designed to search for angle–rate–or–direction–dependent tracking errors. Found direction–dependent errors of magnitude 20 sec. Hypothesized that errors were due to excess signal and saturation of quad detector. (Avalanche detector known to be saturated.) Test: A., Perf.: NA.
T29011	Tracker Calibration	Reduced aperture on R7 to test saturation hypothesis. Remaining direction–dependent error found to be less than 3 sec, limit set by drift of IMU inner gimbal dur–ing test. Closes problem found in T28271.
T29201	Tracker Calibration	Test plagued by erratic tracker outer gimbal readout, tentatively ascribed to bad fine encoder. Some data should be usable. Changed R/D encoder – OK.

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TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 – 11/9/82) (CONTINUED)

Test No.	Title	Notes
T2A061	Tracker Calibration	Test included tilting of Goerz table. Data from R6 was erratic (thru window) with ITRCNT ~20, and R8 still saturated (even some oscillation while viewing R8). Data appears good and analysis in progress; all tracker geometry parameters should be derivable from this data. Test: A, Functions: A.
T29101 T29131	Tracker Thermal	Tracker and LSP exposed to local high temperature environments while tracking retro. Range and angle data recorded. Tracker and LSP demonstrates opposing sensitivities yielding a net range sensitivity of +0.068 cm/delta degree F. Angle sensitivity is −0.275 $\widehat{sec}$/delta degree F. Test: A, Performance: A.
G29281 G2A043	Gyro Polar Calibration	Sequentially hold each gyro north then south polar to check bias and scale factor stability. Test: A, Performance: A.

8210K380-3

TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 – 11/9/82) (CONTINUED)

Test No.	Title	Notes
C2A041	IMU C&A	Inverted C&A. Real-time data indicated systematic error. Post-processed data indicated relatively good state estimation stability and low error in magnitude of g (EMAGG ≅ 2.0 peak). Performance not good enough for mission. Test: A, Performance: NA.
C2A131 C2A151	IMU C&A	Inverted C&A's. Gyro statistics opened to allow more noise and trend. Real-time data much improved relative to C2A041 in terms of lower systematic errors and lower peak. EMAGG ≅ approximately 2.0 real-time. Performance not good enough for mission. Possible problem with X and/or Y-gyros indicated by post-processing of data. Test: A, Performance: A.
D29211 D29271	Check Software for 5 Minute C&A	Software changed from 1-minute to 5-minute Kalman cycle time for C&A. Test: A, Software: A.
F29291 F2A191	Flight Software– IMU Stand-Alone Navigation	Functional check of software transferred from Amdahl/ VAX to PDP 11/70 M. Includes unaided navigation and tracker search/lock-on using nav. results. Test: A, Software Functional: A.

8210K380-4

TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 – 11/9/82) (CONTINUED)

Test No.	Title	Notes
C2A111 C2A121 C2A171	Carousel Test	Test gyro bias, scale factor states and stability through 90 degree carousel. Test: A, Performance: NA.
H2A211	Carousel Heading Sensitivity	Observe gyro bias and platform misalignment in real-time test and post-process for the same terms plus gyro scale factors. System problem at approximately 6 hours–problem in parameter estimation on all three gyros. Post-test gyro torquing check at 0, 0, 0 gimbal angles indicated approximately 10 meru shift in Y–gyro bias drift. Conclusion: Replace Y-gyro and turn IMU upright. Test: NA, Performance: NA.
H2B011	Carousel Heading Sensitivity	Upright orientation – Y-gyro changed. Large apparent shift in X-gyro bias. Suspect test algorithm first and possible problem in transformation resolver electronics second. Test: NA, Performance: NA.

8210K380-5

TABLE 4-2.

APTS TEST LOG SUMMARY (7/20 - 11/9/82) (CONTINUED)

TEST NO.	TITLE	NOTES
H2B031 H2B041	Carousels	Eliminated slew-mode operation of IMU. Conducted two carousels with same initializations. Excellent real-time repeatability for portion of test when estimator was turned on. Post-processed results indicated much more stable performance than prior results. Test: A, Performance: A.

TABLE 4-3.

APTS TEST LOG SUMMARY (5/18/82 – 7/20/82)

Test No.	Title	Notes
A25181 A26081 A26082	Accelerometer PSDs	OK – power spectral density data compares well with previous runs
T25201 T25241	Tracker Search	OK – tracker search and lock-on performs properly. Low-speed and high-speed scans are satisfactory (0.06–1 rad/s)
T26151 T26152	Retro Preliminary Calibration	OK – measured range and angles to target retros to augment range finder and theodolite data and extract resolver harmonic errors
T26181 T26182 T26183	Preliminary Tracker Cal and Align (Partial)	OK – range and angle data for measurement of tracker gimbal angle misalignments and resolver harmonic errors
C26291	Abbreviated IMU Calibration & Alignment (Diagnostic)	OK – IMU performance good. Test run to check for previously suspected bug in (A) torquing routines or (B) erroneous initial conditions in early C&A attempt (previously reported test number C25091). No software bug detected (error type A)

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TABLE 4-3.

APTS TEST LOG SUMMARY (5/18/82 – 7/20/82) (CONT.)

Test No.	Title	Notes
C26292	Abbreviated IMU C&A (Diagnostic)	OK – IMU performance good. Test run with purpose-ful error in initial condition to check hypothesis (B) in previous test. Test abort did not occur
C26301	IMU C&A	NG – purposely aborted C&A after approximately 8 hours when error was detected in initial conditions. IMU performance OK to end of run
C26302 C26303	IMU C&A	NG – system functions ceased after approximately 24 hours of good IMU performance and telemetry data. Suspected hardware problem with computer terminal on 3rd floor of lab. Terminal malfunction confirmed on 7/6/82 as probable causes of computer "hang-up"
C27071	IMU C&A	OK – completed functional C&A with normal termi-nation. This test forms baselines for comparison analysis with future C&As. Telemetry data also indicated normal system operation

TABLE 4-3.

APTS TEST LOG SUMMARY (5/18/82 – 7/20/82) (CONT.)

Test No.	Title	Notes
C27091	IMU C&A	NG – normal operation until near termination. Final inner gimbal angle (azimuth) was approximately 110 degrees vs. expected value of 0 degree. Software bug suspected since correct commanded rate of z-gyro was overwritten in computer exactly coincident with last C&A segment
T27131	Tracker/IMU Gimbal Calibration	OK – recorded tracker and IMU data while locked onto each of seven retros for purposes of extracting gimbal angle biases and resolver harmonics

TABLE 4-4,

APTS TEST LOG SUMMARY (2/12 – 3/12/82)

Test No.	Title	Notes
D22121	Accelerometer Diagnostic Cals	OK – Bias, scale factor and misalign data on accelerometers converge as required.
A22121 A22131 A22132	Accel. Data: 1 min theta dot and 80 msec theta data	OK – Data stability compares well with previous programs. Indicates instrument performance ok to conduct C&A. IMU in slew mode.
A22160	Accel. Data; 1 min samples, theta dot	OK – Manually-collected data with IMU in stab. mode. Okay to conduct C&A.
T22160	Tracker HW/SW Integration	OK – Tracker transition from search to lock-on target.
T22171 T22181 T22191	Tracker Search	NG – Hi-speed search erratic. H/W change needed in R/D converter. NG – Open loop gimbal servo response too slow. OK – S/W performs lo-speed, small scan as required for target lock-on.

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TABLE 4-4.

APTS TEST LOG SUMMARY (2/12 – 3/12/82) (CONT.)

Test No.	Title	Notes
C22181	First Functional C&A attempt on IMU	NG – Filter diverged after 22 min; suspect inadequate initialization of a priori values.
G22181	IMU Open Loop Thermal Stability	OK – Gyros in 2-phase wheel power mode. Gimbal servos off. Thermal control maintained.
B22211	IMU Gimbal Bias Measurement	OK – Estimation of gimbal biases and nonorthogonalities at 13 different platform attitudes. Compares well with manually observed values.
G22231	IMU Thermal Control Test	OK – Evaluated thermally worst-case stable member attitudes required by C&As. Indicates thermal control can be maintained for conducting C&As at 95° F ambient, if required.
		Evaluated control and stability at IMU operational attitude (0, 0, 0 gimbal angles) and elevated ambient temperature.
		Overnight test computer stop being investigated.

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TABLE 4-4.

APTS TEST LOG SUMMARY (2/12 — 3/12/82 (CONT.)

Test No.	Title	Notes
T22241	Target Tracking Stability	OK — Baseline test; AGC disabled, target at approximately 200 ft through lab window. Approximately 2 sec pk-pk per axis.
T22251	Tracker Ranging	OK — Tracker range data being received and processed through time interval meter.
		NG — DMA display is nonzero with zero data input. Actual range data not displayed. Zero is ok after replacement of DMA interface card in EEU. S/W problem in range data being investigated.
G22261 G22262	Thermal Test (Cont.)	OK — Thermal control maintained up to 120°F ambient at nominal IMU operating attitude (0, 0, 0°). Gyro wheel power glitch during overnight testing under investigation.

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TABLE 4-4.

APTS TEST LOG SUMMARY (2/12 – 3/12/82 (CONT.)

Test No.	Title	Notes
T23010	Tracker Invalid Check During Search	NG – Invalid returns caused Tracker Search Routine to be prematurely terminated. Valid return discrete can be reset in EEU at 3 of 8 returns instead of 1 of 8. Suspect problem is due to scattered returns due to poor viewing window (lab window) and target surroundings being at close range (approximately 200 ft).
T23011	Tracker Stability & Ranging Test	OK – Range data at DMA Display corresponds with Time Interval Meter. This covers problem found in T22251 which was due to wiring error in DMA Interface Card.
T23030	Tracker Search	OK – Hi-rate search (approximately 1 rad/s) functions properly except for overshoot at each end of scan and pauses during scans. Check for hardware bug in 9-bit coarse encoder.
		NG – Lo-rate scans has oscillations and unbalanced speed in opposite directions. Check electronic and mechanical balances.

8203D218-28

TABLE 4-4,

APTS TEST LOG SUMMARY (2/12 – 3/12/82 (CONT.)

Test No.	Title	Notes
T23050	Tracker Search	OK – Hi- & lo-rate scans function. Lo-rate works at 0.08 rad/s; need 0.06 rad/s. Change mechanical balance. Closes out problem T23030 except for overshoot.
		NG – Still getting invalid setting of "Data Valid Bit." Appears as function of gimbal positions. Suspect reflections from garage and window. Check threshold setting and "N-of-Eight-Returns" setting.
C23051	Lab. Cal. & Align	NG – Aborts after approximately 14 minutes during "Go-To-Position" Segment. Check a priori gyro stats, elimination of measurement residuals test and closed-loop Go-To-Position segment.
T23080	Tracker Moding & Tracking	OK – Computer moding up to and including switching from search to tracking verified.

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TABLE 4-4.

APTS TEST LOG SUMMARY (2/12 – 3/12/82 (CONT.)

Test No.	Title	Notes
T23089	Tracking Thermal Test	OK – Took approximately 1.5 hours of high rate scan power input to reach maximum temperature of 131°F deg F. AGC not on. Normal scan time approximately 1 minute.
I23080	IMU Moding	OK Verified computer-controlled moding.
G23100	Gyro Diagnostic Calibration	OK – Ten stable member positions used to collect gyro scale factor, bias and g-sensitive estimates for C&A a priori inputs.
A23100	Accelerometer Diagnostic Calibration	OK – Scale factors compare well with previous data.
C23111 C23112 C23113	Lab. C&A	NG – Problem suspected in S/W – filter looks OK for first 10 minutes of operation.

8203D218-30

TABLE 4-4.

TRACKER TEST LOG SUMMARY — 5th FLOOR RANGE
(11/23 — 2/12/82; TRANSFER TO SYSTEM LAB)

Test No.	Title	Notes
T100	Tracking & Ranging Test	OK — Verified closed-loop tracking and ranging at approximately 162 m.
T101	Tracker Range Bias Measurement	OK — Bias data extracted with known test range distances. Reasonable comparison with calculated values.
T102	Long Range Tracking	OK — Range stability at 1120 m measured. Warmup expontential measured. Data adequate to continue to system integration.
T103	Tracker versus Retro Types	OK — Range 1120 m. Solid, circular aperture retros found adequate at high incidence angles. "Bicycle" restros are NG.

8203D218-10

Table 4-4,

TRACKER TEST LOG SUMMARY – 5th FLOOR RANGE
(11/23 – 2/12/82; TRANSFER TO SYSTEM LAB) (CONT.)

Test No.	Title	Notes
T104	Tracker Beam Alignment Test	NG – Procedural difficulty in adjusting large folding mirror on tracker. Small laser emitter mirror more easily adjusted.
T105	Tracker Beam Mapping Tests	NG – Determined that beam brightness profile not maximized relative to detectors.
T107 T108 T109 T109R	Beam Alignment	OK – Maximized beam return magnitude and symmetry relative to angle and range detectors. Closes out T104 and T105 problems. Additional "tweaking" available if needed

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TABLE 4-5.

APTS TEST LOG SUMMARY (3/12/82 – 5/12/82)

Test No.	Title	Notes
C23121 C23131 C23132 C23171 C23181 C23191 C23192 C23221	IMU Calibration and Alignment	NG — software debugging runs — open–loop and closed–loop tests. Located and fixed torque–timing problem, etc.
C23222 C23241	C&A	OK — completed ~52 hours of open–loop C&A. Post–processed data agrees well with gyro diagnostic cals and with instrument–level gyro test data. Closes out open–loop C&A test problems C23121 through C23221.
C23291 C23311	C&A	OK — adjusted gyro max. torque level allowed by soft–ware. IMU misalignment data converging as required.
C24041	C&A	NG — C&A closed–loop test performing well — executive parity error at 22.5 hours stopped computer. Ran memory diagnostic tests — changed one computer module.
C24131	C&A	NG — Z-gyro instability apparent. Nineteen unit shift in Z-gyro. Axial flotation signal slow in centering.

8205A265-1

TABLE 4-5.

APTS TEST LOG SUMMARY (3/12/82 – 5/12/82) (CONTINUED)

Test No.	Title	Notes
G24141	Gyro Stability Test	NG – checked Z-gyro for ramping and transients. Excessive ramp observed.
W24221	IMU Warmup Test	OK – measured approx. 22 hours from turnon to functionally stable gyro performance. Compares well with previous programs.
G24269		OK – gyro diagnostic cal. – gathered a priori data for C&A
C24271 C24281	C&A	NG – gimbal angles required by C&A not achieved. Located and cleared blockage of gimbal. Note brief open servo on Accel. No. 2.
C24291	C&A	NG – C&A aborted; accelerometer No. 2 servo opened. Replaced instrument. Replaced X-gyro to isolate wheel power supply variations.
C25061	C&A	NG – outer gimbal missed desired attitude by 15°. Apparent hangup due to gimbal stop. Run aborted after approx. 24 hours of open-loop run. Restarted C&A.
C25071	C&A	OK – ran through entire calibration sequence open loop. Aborted run during gimbal rewind in order to start closed-loop run.

8205 A265-2

TABLE 4-5.

APTS TEST LOG SUMMARY (3/12/82 – 5/12/82) (CONTINUED)

Test No.	Title	Notes
C25091	C&A	NG – software bug in this C&A version. Selected another version for next test.
C25092	C&A	OK – first successful closed-loop C&A. Closes out C23121 through C23221.

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TABLE 4-5.

LASER TRACKER TEST LOG SUMMARY (3/12/82 – 5/12/82)

Test No.	Title	Notes
T110 T111	Long–Range Tracking	OK – tested tracking with and without AGC at 1 mile. Also, tuned gimbal servos for null when tracking and checked performance with servo integrator engaged and adjusted threshold for quiet performance.
T112	Tracking Characterization	NG – large (60 cm) range variation (drift) observed during 105 hours of continuous operation. Data apparently correlated with temperature variation. Adjusted threshold and constant fraction discriminator.
T113	Thermal Sensitivity Baseline Test	OK – baseline test indicated stable range data when room ambient temperature held to a few degrees of variation (31 hours). Standard deviation of data OK (8–10 cm).
T114	Thermal Variation Test	NG – isolated apparent thermal sensitivity to LSP. Range variation of approx. 1.5 cm/$^\circ$F at approx. 162 m is apparent vs. desired value of approx. 0.5 cm/$^\circ$F (i.e., 2 in 10^5 parts at $\pm 10^\circ$ F temperature variation.
T115	LSP Component Thermal Variation	OK – applied heat to individual LSP components; checked range variation vs. power supply variations. (Also, adjusted output pulse triggering.) No thermal sensitivity detected.

TABLE 4-5.

LASER TRACKER TEST LOG SUMMARY (3/12/82 – 5/12/82) (CONTINUED)

Test No.	Title	Notes
T116	Long–Range Acquisition and Tracking	OK – testing with restricted retro apertures demon-strates that tracker operation at worst-case range (6,000 ft) and angle of array viewing is practical.
T117	Thermal Variation Repeat	NG – reproduced apparent correlation of range data with ambient temperature.
T118	Range Stability Test (First Floor Lab)	OK – clamped gimbals and collected range data with computer.
T119	Range Finder/Tracker Range Stability Test	NG – used USGS range finder to test range stability to garage roof coincident with tracker ranging. Tracker drift approximately 6 cm zero to peak. Range finder <0.5 cm in first 4 hours.

5. REVIEW OF TEST TECHNIQUES AND GENERAL RESULTS

5.1 GENERAL

In this section we review some of the general results of the
Lab. Test Program on APTS. Preparatory to the results
review, we outline the test techniques for the primary sen-
sor subsystems; i.e., the IMU, Tracker and Laser Profiler.
In particular, the section deals with performance test tech-
niques and results - the functional test results were previ-
ously reported under separate cover during the Phase 5 and
Transitional Phase of the contracted program.

5.2 REVIEW OF IMU C&A TEST TECHNIQUE

The C&A test involves rotation ('tumble') of the IMU stable
member relative to the known gravity and earth rate vectors
in the laboratory as the calibration function of the various
subsystem states, such as accelerometer scale factor, bias,
etc.. There are 57 of these states calibrated by the conti-
nous online Kalman Filter (Table 5-1). After calibration,
the alignment function is accomplished by rotation of the
stable member in local azimuth such that the attitude in
north-east-down coordinates can be accurately determined.
The particular benefit of the azimuth rotation section of
the test is that the gyros are not subjected to variation in
the gravity vector magnitude and therefore alignment can be
both measured and commanded to the desired attitude.
Because of the system's rotional observation of the varying
earth rate vector, the stable member azimuth misalignment
and east gyro drift terms can be separated by the filter.
Also, the gyro bias drift, in terms of a 'lumped
coefficient' which includes both g-sensitive and
g-insensitive components, can be estimated. Finally, the
test technique is completed with an earth-fixed segment
which allows transient systematic terms to settle.

Figure 5-1 illustrates the foregoing C&A procedure in which
stable member and instrument estimation and control func-
tions are accomplished.
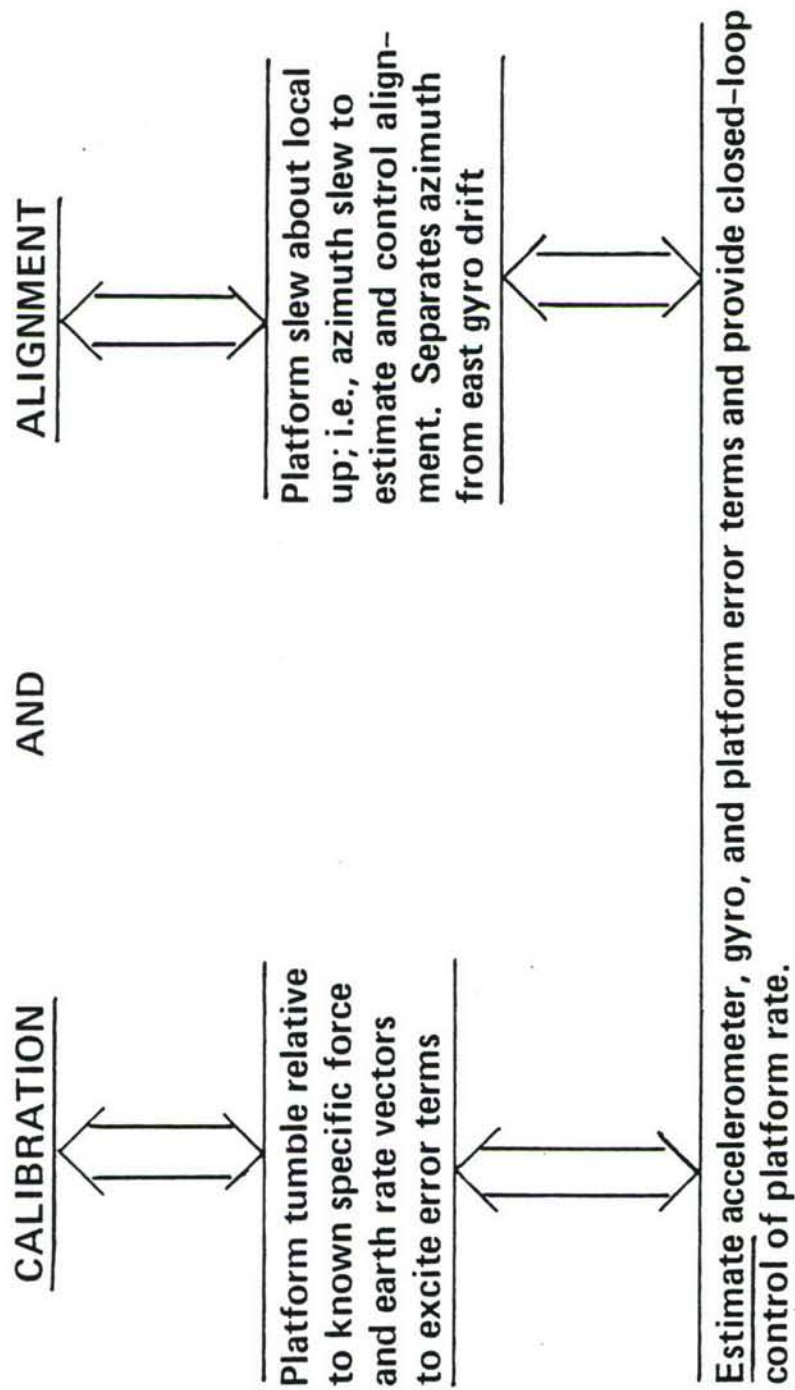
Table 5-1

CALIBRATION AND ALIGNMENT OUTPUTS

State No.	States in Filter
1-3	Platform misalignment ψ
4-6	ACCEL bias
7-9	ACCEL scale factor
10-12	ACCEL IA misalignment
13-15	Gyro bias
16-18	Gyro scale factor
19-24	Gyro IA misalignment
25-33	Gyro g-sensitive coefficient
34-36	ACCEL FX1 g-squared coefficient
37-39	Gyro torquer nonlinearity
40-42	Gyro DF ramp coefficient
43-57	Gyro g-squared coefficient

- Filter states

- Error in magnitude of g
- Platform misalignment data
- Filter $\vec{g}$ residuals
- Trajectory data
- Functional data

Figure 5-1.   IMU CALIBRATION AND ALIGNMENT

CALIBRATION   AND   ALIGNMENT

Platform tumble relative to known specific force and earth rate vectors to excite error terms

Estimate accelerometer, gyro, and platform error terms and provide closed-loop control of platform rate.

Platform slew about local up; i.e., azimuth slew to estimate and control alignment. Separates azimuth from east gyro drift

At the heart of the C&A test is the online Kalman filter which permits the continous estimation of instrument coefficients and control of the stable member. Figure 5-2 is a block diagram of the filtering process. The angular data (theta) from the accelerometers is first processed by a prefilter which provides a cubic fit of the data and outputs an estimate of the value at the midpoint of the filter cycle (each cycle is five minutes in duration). Then, the measured value, WPIG, is differenced with a predicted value to provide a residual, Z. This residual is employed to update the system state in an optimal fashion, as shown. Additionally, a state covariance estimate is deterministically computed for each state based upon the particular trajectory used for the test; i.e., the observability of the various states. Having updated the states and observed the difference between commanded orientation and measured orientation, the filter makes an estimate of the drift of the stable member during the five minute cycle and estimates the misalignment rate. These parameters are then used to provide a constant torque to the stable member over the next filter cycle. Thus, in combination with a reference trajectory, the torque is iteratively adjusted each cycle until the residuals and the misalignment become small; i.e., the measured and predicted values agree. This iterative estimation and control procedure requires approximately 48 hours for a complete C&A test or 12 hours for an abbreviated test such as a carousel in azimuth. The former test permits calibration of 57 states while the latter test provides calibration of 21 states.

5.3 LASER TRACKER CALIBRATION

The calibration of the Tracker involves measurement of range bias, computation of scale factor, determination of gimbal non-orthogonality, computation of displacement vector with respect to the IMU coordinate frame and estimation of gimbal angle encoder errors (Tables 5-2 and 5-3).

The Tracker range bias was measured by comparing Tracker range data with the independantly-measured distance over a calibrated range. A calibrated range was provided by the USGS on the fifth floor of the Draper Lab. (Fig 5-3).

The scale factor of the Tracker was computed from the known speed of light and modified by the difference in APTS clock frequency from the exact clock value (i.e., unrounded value).

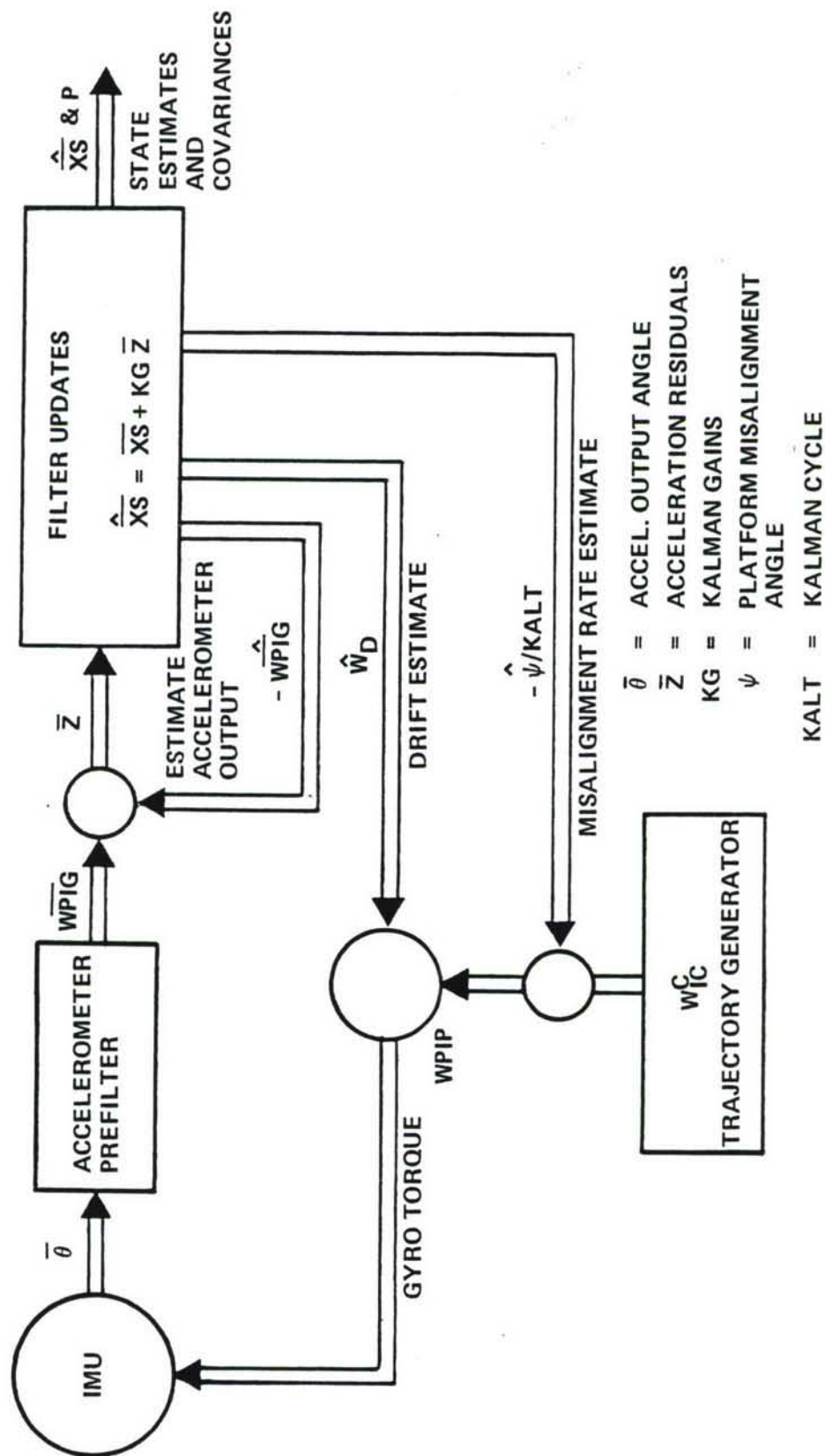Figure 5-2. Calibration & Alignment Block Diagram

$\hat{\overline{XS}}$ & P

STATE ESTIMATES AND COVARIANCES

FILTER UPDATES

$\hat{\overline{XS}} = \overline{XS} + KG\,\overline{Z}$

ESTIMATE ACCELEROMETER OUTPUT

$-\widehat{WPIG}$

$\hat{W}_D$

DRIFT ESTIMATE

$-\hat{\psi}/KALT$

MISALIGNMENT RATE ESTIMATE

$\overline{Z}$

$\overline{WPIG}$

ACCELEROMETER PREFILTER

$\overline{\theta}$

IMU

GYRO TORQUE

WPIP

W_{IC}^C

TRAJECTORY GENERATOR

$\overline{\theta}$ = ACCEL. OUTPUT ANGLE

$\overline{Z}$ = ACCELERATION RESIDUALS

KG = KALMAN GAINS

ψ = PLATFORM MISALIGNMENT ANGLE

KALT = KALMAN CYCLE

J. HAND
28 September 1982

CSDL

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Table 5-2

LASER TRACKER CALIBRATION IN LABORATORY

Parameter Calibrated	Technique	Notes
Range Bias	Compare tracker data with independently measured target distances as calibrated by USGS	See fifth floor test range vugraph
Scale Factor	Speed of light calculations and clock calibrations	
Nonorthogonality of Gimbal Axes and Angle Encoder Zero and N-Speed Encoder Harmonics	Compare tracker vs IMU and rotary table at various orientations while tracking selected targets. Evaluate tracking data for known angle encoder harmonics	See lab interior and exterior target sets vugraphs
Displacement Vector	Calculations from mechanical tolerances between tracker and IMU gimbal intersections	Also estimated from retro tracking data taken in lab
Surveying Angles	Evaluate angle noise and drift characteristics from static and dynamic tracking data using lab targets	Computer-collected data at 200 Hz rate

Table 5-3

LASER TRACKER CALIBRATION REQUIREMENTS

Parameter	One Sigma Measurements		
	In-Lab.	In-Flight[1]	Post-Processed
Range Bias Uncertainty	0.2 cm	---	0.2 cm
Range Scale Factor Uncertainty	3×10^{-6}	6×10^{-4}	3×10^{-6}
Nonorthoganality of Gimbal Axes and Zero Point Encoder Errors	$\approx 10^{-4}$ rad	6×10^{-4} rad	2×10^{-5} rad
Displacement Vector Errors	0.5 cm	---	0.5 cm
N-Speed Encoder Errors	TBD	---	2×10^{-5} rad
Surveying of Retros	$\approx 10^{-4}$ rad	---	$\approx 10^{-6}$ rad

(1)   Absolute limits to assure model linearity.

(2)   --- Indicates insignificant error magnitudes.

Figure 5-3. FIFTH FLOOR TEST RANGE

NOTES:

1. All points are shown as approximate locations.

2. R1 through R4 are retro locations during test and theodolite surveying.

3. Measure and record all angles a through k.

4. R1, R2, T1 and R4, R3, T1 form two straight lines L1 and L2, respectively.

5. Servo closure and stability can also be tested on this range.

TO RETRO
AT ≈ 5260 ft

GARAGE
ROOF

R4

D2

R3

h

g   f

i

j

D1

a

b

R1

c

d

e

R2

L1

L2

D3

D4

k

T1
TRACKER

LAB
5274

SCALE 100'

- 42 -
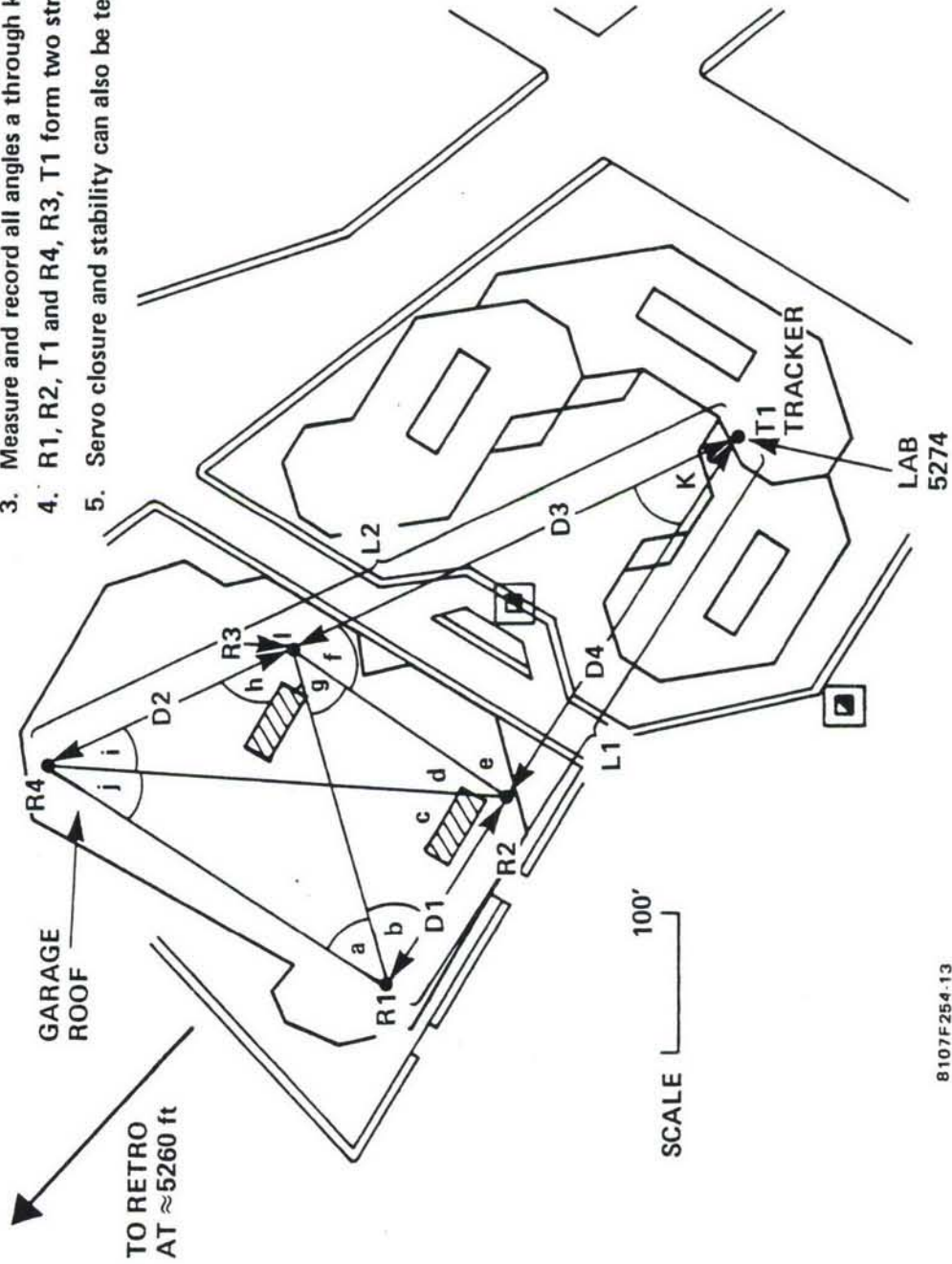
The non-orthogonality of the gimbals, outer and inner, was determined from recorded data using various combinations of angles to observe selected targets. A set of interior and exterior retros was independently calibrated for this purpose (Figs 5-4 and 5-5). This type of test also served to provide data for the estimation of gimbal encoder harmonics.

The displacement vector between Tracker and IMU center was computed from estimation of mechanical tolerances and verified roughly using the retro set mentioned above.

Periodically, Tracker gimbal data were recorded while locked onto a retro and then plotted vs. time in order to verify stability. Also, a thermal test of the Tracker verified its ability to track retros under variations of temperature to +/- 10 deg F. of the nominal operating temperature.

Finally, the Tracker was used in conjunction with the IMU and Computer and the software to update the inertial navigation function from a rotating base. During this test, various base rates up to 3 deg/sec were exercised while the Tracker acquired and tracked preselected retros as required. Also, the tracking function was checked to demonstrate 'hang-on' capability up to base rates of 6 deg/sec. In addition to this maximum rate test, a maximum range test was performed by statically tracking retros at the distance of approximately one mile.

5.4 LASER PROFILER BORESIGHT CALIBRATION

The objective of the Profiler Boresight Calibration is to measure the instrument line of sight in navigation base coordinates such that the profiled data will be in a known frame of reference. For purposes of this test the boresight is defined as the line between the center of the laser diode and the center of the transmission lens. Note that this is simply a convenient calibration line for the test as designed.

The test technique is to set a retro at sample distances along the maximum return line measured with the Profiler and then track the same retro with the Laser Tracker. This technique permits the determination of the boresight in navigation base coordinates as shown by Fig 5-6. Note that this test will be conducted at the Bedford flight facility as it requires long baselines.
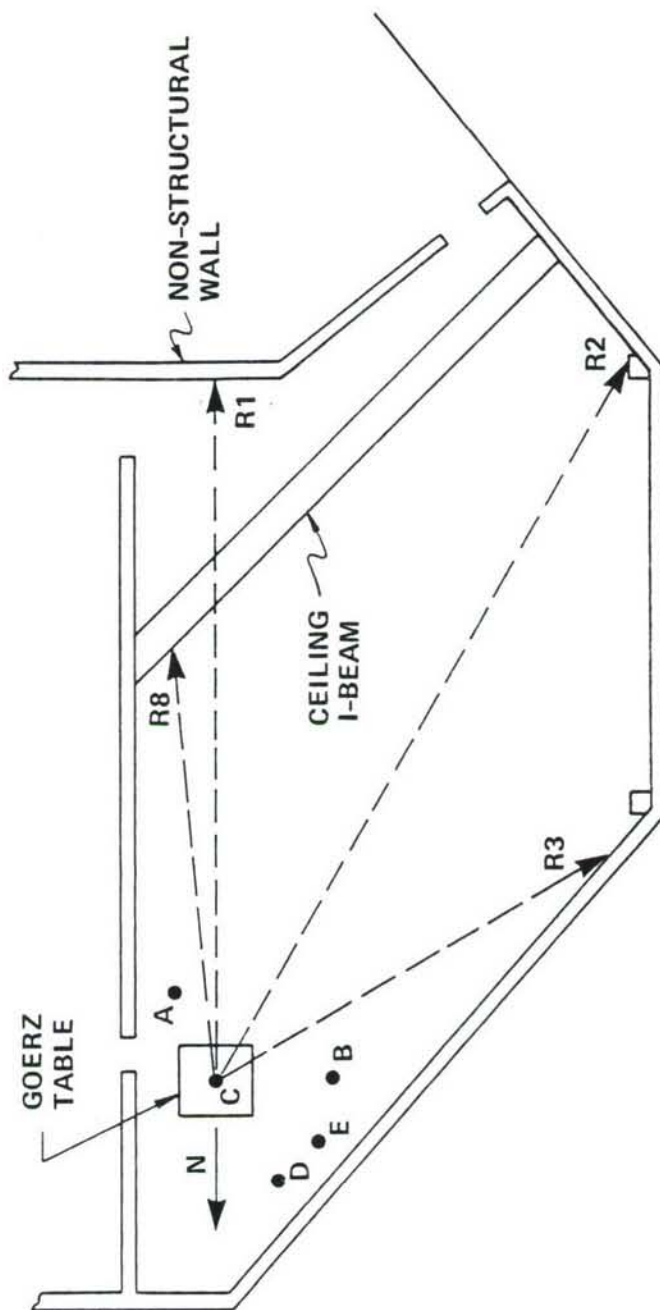
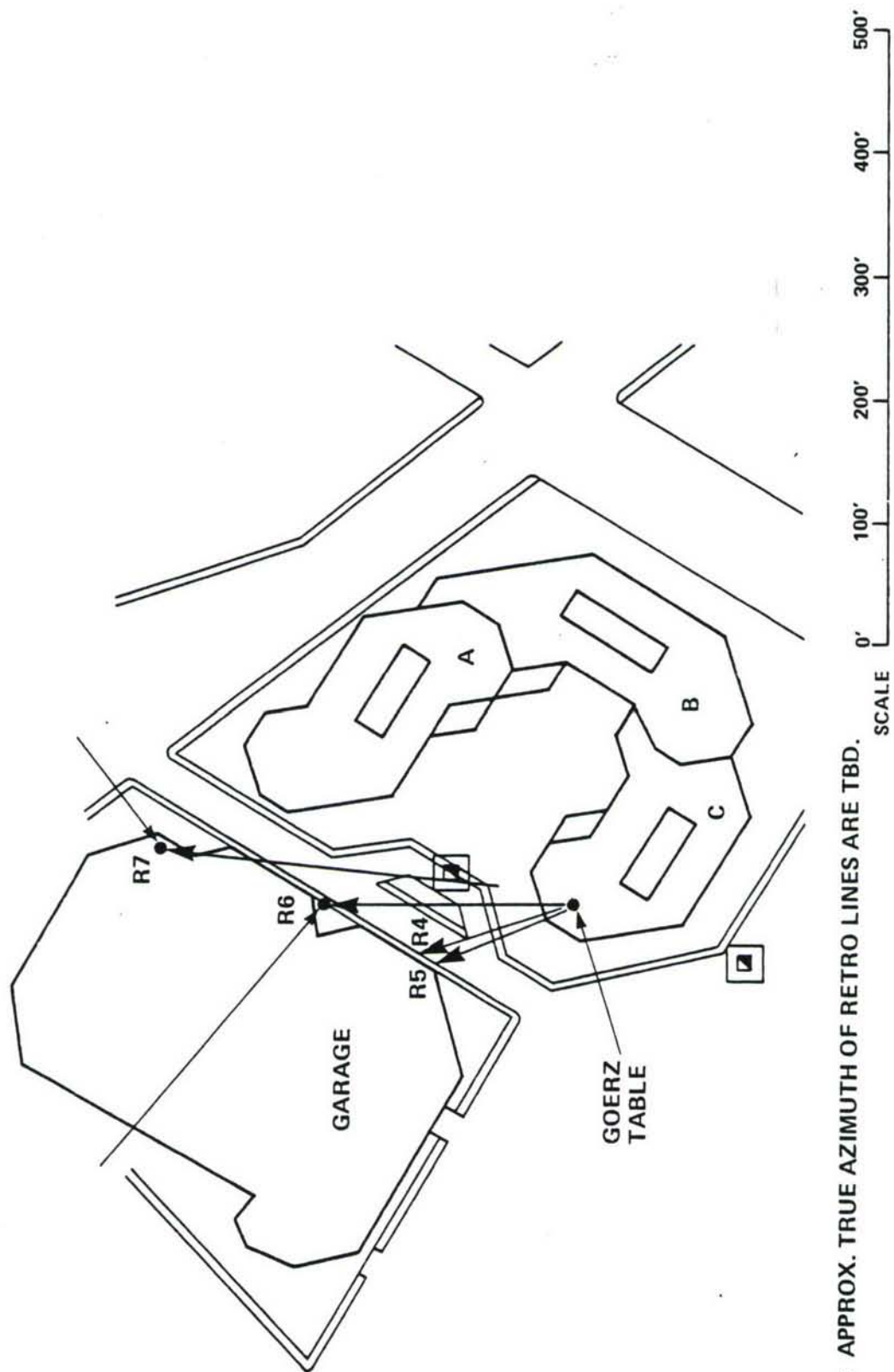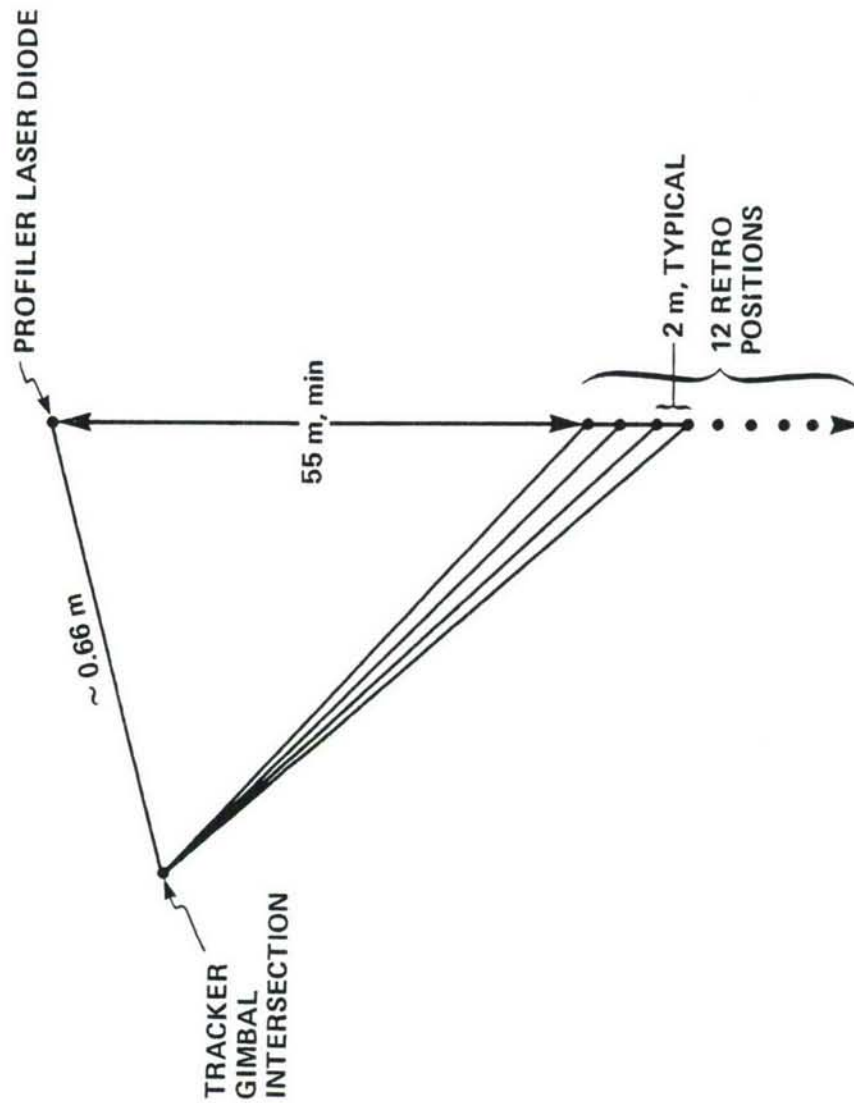Figure 5-4. INTERIOR RETROS
LAB 1304B

8207B245-3

Figure 5-5. EXTERIOR RETROS

NOTE: APPROX. TRUE AZIMUTH OF RETRO LINES ARE TBD.

SCALE

0'   100'   200'   300'   400'   500'

GARAGE

GOERZ
TABLE

R7
R6
R5   R4

A
B
C

8207B245-2

Figure 5-6. PROFILER BORESIGHT TEST

MEASUREMENT: PROFILER BORESIGHT LINE OF SIGHT
IN NAVIGATION BASE COORDINATES.

PROFILER LASER DIODE

~ 0.66 m

55 m, min

2 m, TYPICAL
12 RETRO
POSITIONS

TRACKER
GIMBAL
INTERSECTION

NOT TO SCALE

8107F254-10

Limited performance testing of the Profiler was performed at Draper by sighting the instrument onto buildings in the vicinity and then measuring the amplitude of the return pulse. This testing showed that the maximum range of approximately 600 meters was achievable.

5.5 COMPUTER PERFORMANCE

The Flight Computer supported the sensor subsystems in the required APTS functions. The software operated as needed to control the real-time C&A, including the all-attitude version which will be used in the aircraft. Also, the Tracker search and track logic performed properly in conjunction with acquisition and lock-on of retros. The navigation programs were demonstrated in both the inertial-only and the Tracker-aided modes. Throughput and memory allocations of the Computer proved to be adequate in all required operational modes. Occasional synch bit errors have happened and have caused transient failure of the Direct Memory Access function. Test activities have not disclosed a Computer-connected malfunction for this problem. An electronic ground-loop is suspected as the cause of the problem which occurs during power changes such as turning on the time interval counter or plugging in peripheral equipment into the back of the rack. Rectification of the problem is therefore partially procedural in that power changes to the system will be avoided during normal operation. Of course the suspected ground loop cause is also being sought. Software recovery procedures are also being implemented.

5.6 REVIEW OF RESULTS

5.6.1 IMU C&A TESTING

The IMU C&A results approached the quantitative levels of previous programs which employed the same generic class of inertial instruments; thereby indicating that the performance was as expected. The APTS performance goals were also met in the stability and repeatability of the last two Carousel tests and in the IMU drift testing which followed, and in the navigation testing which concluded the acceptance test procedure.

As noted in the test log, there were systematic results in the C&A tests and these results were shown to be related to torque rate and to temperature change over the trajectory. Listed below are the mitigating factors which permitted the APTS to be fielded with this condition: 1. The temperature and instrument performance are within tolerances as demonstrated by the Carousels and this trajectory constitutes a partial calibration and alignment of the system. 2. The torque history of a Carousel approximates that required of flight. 3. Excellent repeatability of the instruments was demonstrated for two identical trajectories, thus indicating proper performance. 4. Two improvements of the thermal control are planned for implementation at Bedford; increase of the fan control gain for tracking temperature compensation required more closely, and inserting a digital control loop into the control. 5. A constant-torque regime for the flight testing is under consideration to negate performance change dependant upon torque change.

5.6.2 LASER TRACKER PERFORMANCE RESULTS

The Tracker demonstrated the low ranging noise and the angular stability on each gimbal axis as required to perform the APTS mission. Fig 5-7 shows the angle and ranging stability of the Tracker before editing and Fig. 5-8 illustrates the same results after editing. The ranging performance represents a stability of approx. 11 cm, single shot, after accounting for sampling frequency.

Thermal test of the Tracker indicated a performance drift of -0.276 cm/deg F in the range data. The Laser Signal Processor demonstrated a compensating change of +0.344 cm/deg F, thereby providing an acceptable net change of +0.068 cm/deg F (see Memo No. APTS I-15-82, by D. McCabe).

Performance of the Tracker was acceptable in retro acquisition and tracking, as previously noted. Also, brief tests of the Tracker in ranging to a retro array at various aspect angles indicated satisfactory results.

The long-range (one mile) Tracker tests along a horizontal direction,which is somewhat more stringent than the intended near-vertical application, showed that the instrument could acquire and track the retro aperture as required and could maintain track of small apertures to approximately one half the acquisition size (roughly, one 2.5 inch dia. retro).
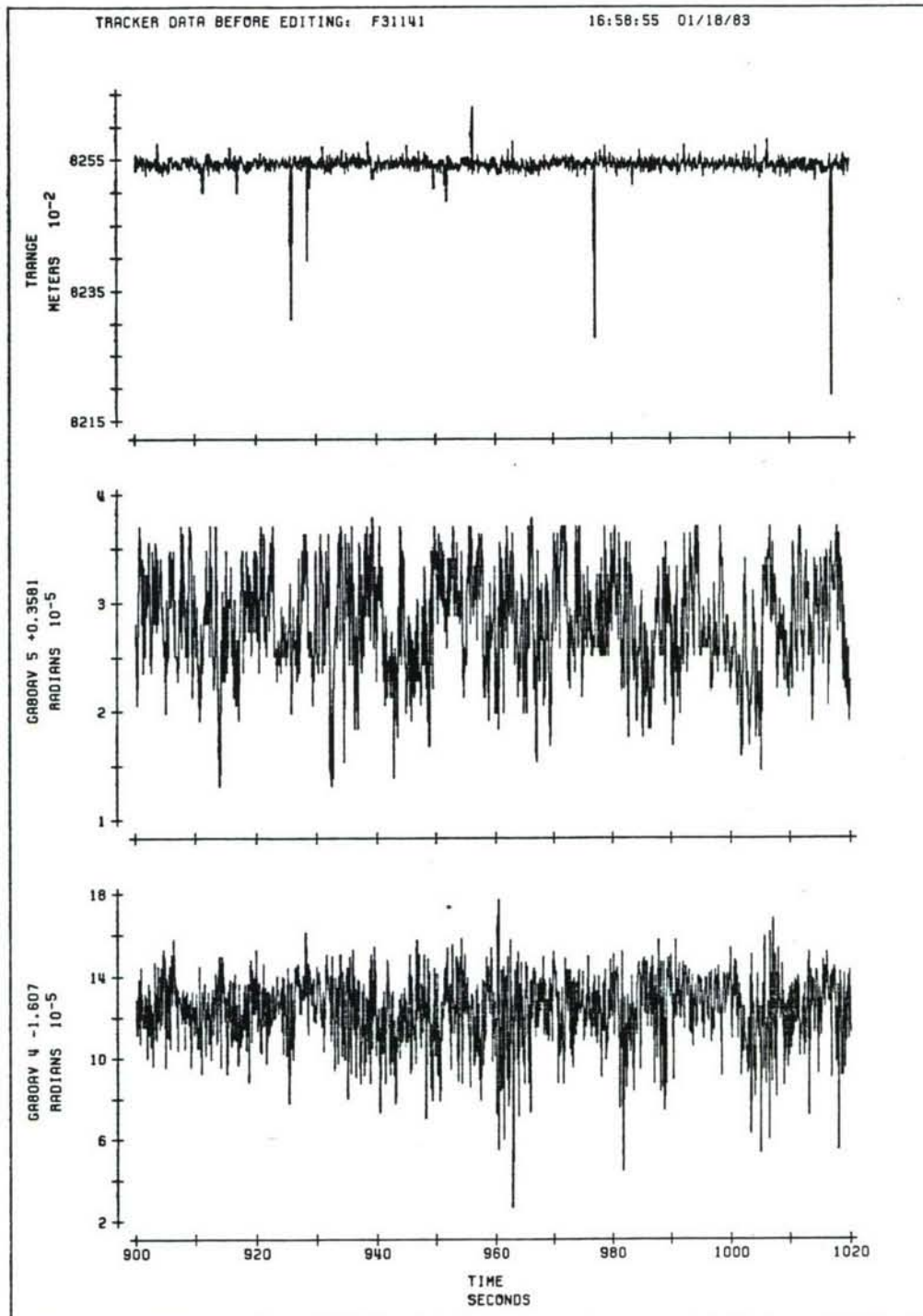
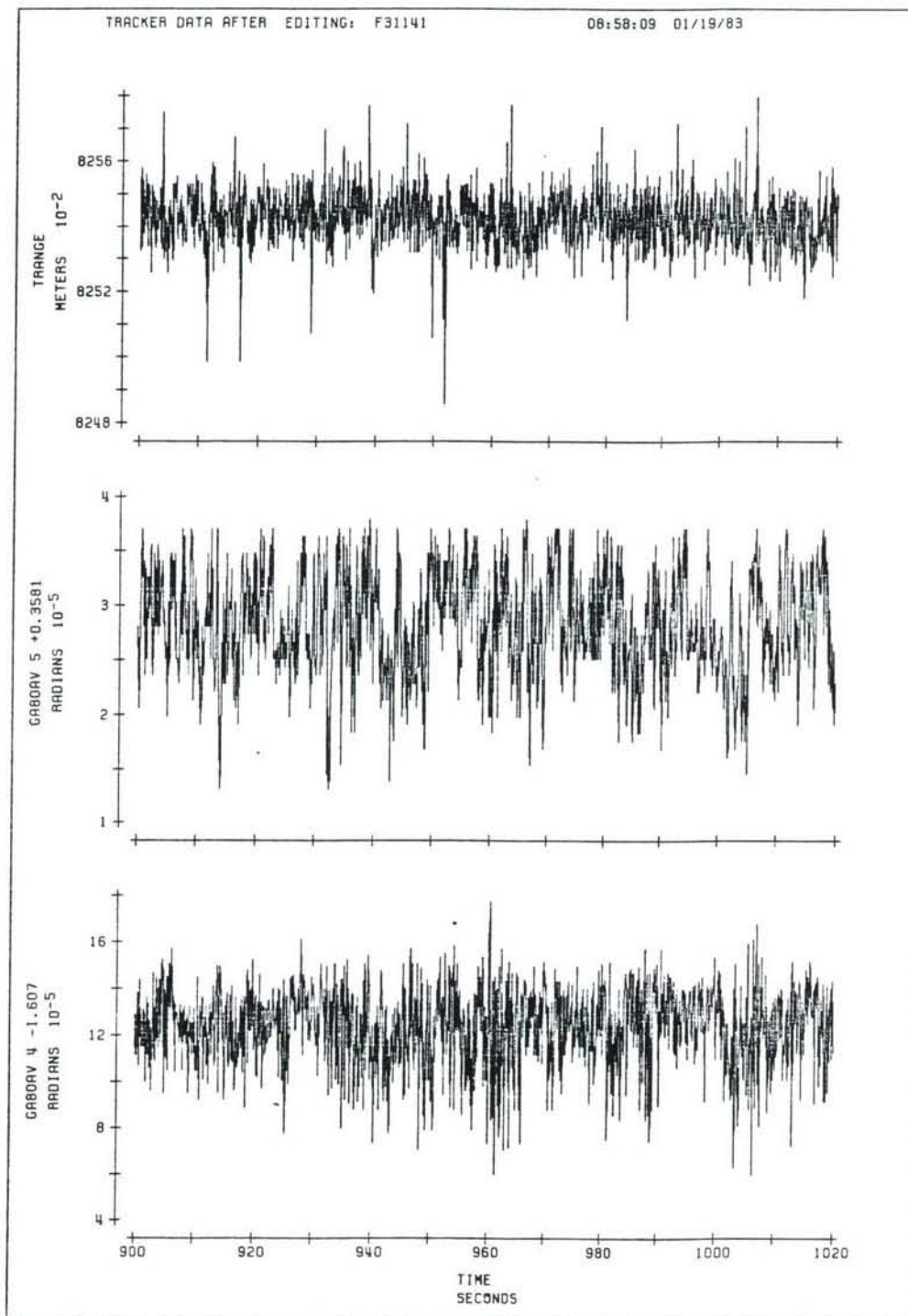Figure 5-7. Typical tracker angle and range data
before editing.

Figure 5-8. Typical tracker range data after editing;
Test No. F31141.

Base-motion tests of the Tracker during the acceptance test-
ing of the APTS indicated the capability to acquire and
track retros at .5, 1, 2 and 3 deg/sec, a satisfactory
result. Maintenance of the target line of sight was accom-
plished through 6 deg/sec, also a satisfactory result.

Experience in testing the Tracker showed that warmup of the
laser is advisable in order to achieve stable ranging and
angle data. Presently, the recommended warmup time is three
hours prior to testing where the finest range stability is
needed. Shorter warmup time is acceptable for functional
tests.

5.6.3 LASER PROFILER PERFORMANCE RESULTS

The Profiler was shown capable of acquiring range data from
a building at a distance of approx. 564 meters. Extrapo-
lation of the data indicated that ranging was practical to
the required distance of 600 meters. The testing was con-
ducted over a horizontal distance, a somewhat more stringent
requirement than the near-vertical application orientation.

6. ENGINEERING PERFORMANCE AND ACCEPTANCE TESTING

6.1 GENERAL

This section describes details of the engineering and per-
formance tests conducted on the APTS during the Lab. Test
Program. First, the procedures for each of the system-level
tests are described; then salient results of the performance
tests are presented. These procedures are also appropriate
for ground testing preparatory to the shakedown and perform-
ance flights of the system to some extent. These procedure
subsets will be also found in the APTS OPERATORS MANUAL with
appropriate modifications to be developed from flight expe-
rience.

6.2. TEST PROCEDURES

6.2.1 INERTIAL SUBSYSTEM CALIBRATION AND ALIGNMENT

When starting the IMU from a cold start, there was often a
small change in the performance parameters; therefore a
repeat of the accelerometer coning test was used to recover
these values when necessary. Then, reinitialization of the
filter was done with the variances opened to accommodate a
larger uncertainty in the instrument values. Typically, the
new initialization employed the end values from the
pre-power down C&A or carousel test, unless, however, there
was expectation of instrument malfunction. In such a case,
a preparatory test such as the Accelerometer Diagnostic Cal-
ibration (ADC) was conducted. This test provided confidence
that the accelerometers were functional and at least coarse-
ly repeatable. Following this procedure, a Gyro Diagnostic
Calibration was occasionally performed for the same type of
benefits. Of course, if either of these two tests indicated
instrument-level problems, then additional diagnostic tra-
jectories were employed to isolate the malfunction to a
particular instrument or its electronics. For example, cer-
tain types of partial carousels and earth-axis polar
calibrations were used to investigate possible instrument
electronics problems, and so forth.

After the preparatory IMU tests, a functional C&A test was
appropriate if the system has been warmed up for a few hours
and the performance-level trajectories were used if there
was a warmup of approximately 48 hours. Further field expe-
rience with the APTS will reveal whether the performance
tests can be successfully done with a lesser amount of warm-
up.

6.2.2 TRACKER PERFORMANCE TEST PROCEDURES

Typically, the Laser Tracker was warmed up for approximately
three hours prior to a performance test. Prior to the start
of the test safety goggles were put on by those in the test
area. Then, Tracker range and angle data were collected on
magnetic tape from the particular test being conducted.
Such data were later post-processed with smoothing and fil-
tering as appropriate. The detailed test procedures, them-
selves, included tracking of interior lab. retros or
exterior retros for various reasons. For instance, the
interior retros were employed in conjunction with the exte-
rior retros in order to determine the gimbal angle
non-orthogonalities relative to the stable member coordinate
frame. In another case the exterior retros were used for
automatic aquisition and tracking tests, since range data
were not collectable from the very close interior retros.
That is, the range gate in the Tracker electronics would not
permit lock-on to these very close targets.

The procedures employed in the step-by-step Tracker testing were first the determination that the instrument could acquire targets and track by manually pointing toward the retros. Then, the automatic search and acquisition software was checked out in combination with the hardware. After these tests were passed, the instrument was verified to be capable of base-motion tracking by use of the rotary table in back and forth directions at various rates. Acquisition was also tested under base motion conditions. Interspersed with these tests were the previously-mentioned thermal tests which showed the Tracker and electronics capable of accurate performance within the required temperature bounds. Finally, after the static and dynamic and thermal tests, the Tracker Subsystem was verified in combination with the navigation software. Engineering-level and then a final acceptance test of the APTS demonstrated that the Tracker Subsystem was ready for additional testing in the field.

6.2.3 LASER PROFILER PERFORMANCE TEST PROCEDURES

The performance tests on the Profiler were conducted in the Fifth Floor Lab. First, the instrument was aligned to provide maximum return from a target surface at range by adjusting the outgoing beam and the detector. Then, the return signal was checked for magnitude and quality. In the First Floor Lab. the Profiler was connected with the Laser Signal Processor and the rest of the system to demonstrate performance with ranging to the garage across the street from that laboratory.

6.2.4 VIDEO SUBSYSTEM PERFORMANCE TEST PROCEDURES

This Subsystem was subjected to a brief series of functional checks in both the First and Fifth Floor Labs. The description of such tests is somewhat academic and will be bypassed since the Subsystem has already demonstrated adequate performance in flight.

6.3 APTS ACCEPTANCE TEST PROCEDURE

The acceptance test procedure is reproduced as Appendix A of this report. The test, as performed, was modified in the manner described here. Such modifications do not alter the fact that the test demonstrated the adequacy of the APTS for further field testing and the verification that the system performance will meet the specified requirements.

1. During the dynamic part of the test, the table rotation was exercized at a maximum of 3 deg/sec. The reason that the rotation rate was not increased to the specified 6 deg/sec level was that the acquisition routine could not complete in the time allowed before the target retro was blocked from the Tracker optics by the Subsystem housing. This is not relevent to the flight requirements in that the retros would not normally be so close to the Tracker. In order to assure that the instrument could 'hang on' to the target during high base motion rates, the test included a subsection where the retro was acquired statically and then the base rotated at the 6 deg/sec rate to observe successful tracking.

2. The C&A trajectory was not employed in the acceptance test; rather the Carousel test was employed. Because of an unacceptable thermal control variation during the trajectory, the former approach was avoided and the Carousel provided the system calibration and alignment which was employed preparatory to the drift and navigation sections of the test. (Note that a digital thermal control loop is being implemented to attempt to minimize the variation during the C&A Trajectory.

3. The 'alignment' section of the test at the conclusion of the Carousel was not employed; rather the drift test was entered simply by freezing the torque words at the appropriate moment. This was a procedural modification only.

4. The IMU was not eccentrically mounted on the rotary table for the first acceptance test run; this was accomplished in the second run with acceptable results from both runs.

5. There was no necessity for inserting lab. realignments as had been originally planned; the target acquisitions were achieved without them.

6.4 DETAILED ENGINEERING TEST RESULTS ON IMU

6.4.1 IMU CALIBRATION AND ALIGNMENT RESULTS

During this test the stable member was rotated in the gravity field to cardinal up/down positions for each accelerometer and through a rotation relative to the earth rate vector which provided excitation of the gyro error terms. During the up/down rotations of the accelerometers the instruments passed through the horizontal zero-g orientation. In this orientation the power change within the instrument caused variations in temperature. Such variations then caused small performance changes which, while not deleterious from a functional view, were roughly two to four times larger

than the desired performance. The systematic character of these disturbances is exemplified by Figure 6-1.

Disturbances of the sort illustrated above were less serious in the Carousel trajectory because the instruments are not rotating in the g-field and thus power and temperature changes are lower; especially with the improvement in the thermal control loop which resulted from moving the monitoring thermistor to measurement of the stable member metal temperature rather than the air temperature. Thereafter, the performance results proved accepatable when using the Carousel, as indicated by Fig. 6-2.

Correlation between the gyro torque application and gravity residual was also observed. This problem is of second order importance in the flight trajectories where torque changes are relatively small. However, it is primarily being addressed by implementation of a constant-torque regime for flight where there will be no changes throughout flight.

Important characteristics of the results of the C&A tests are that the state estimations were accomplished with acceptable repeatability and were well calibrated as indicated by small variations near the end of specific tests. These data are not presented here for security reasons; the results may be reviewed by authorized personnel as permitted by USGS.

The stable member control, using in a closed-loop manner the results of the state estimates, also proved acceptable as demonstrated by freezing the gyro torque commands at the end of a Carousel and observing drift over the ensuing 2.5 hours (approx. flight mission duration). This was additionally demonstrated by low platform drift during the in-place navigation following the drift tests. Such data are exemplified by the results of the acceptance tests which will be discussed shortly.

In summary, then, the engineering performance results on the C&A proved acceptable because the estimation, control and repeatability functions were accomplished.

6.4.2 LASER TRACKER ENGINEERING PERFORMANCE RESULTS

The general results of the Tracker tests have been given and are exemplified by the previously-referenced Figs. 5-7 and 5-8. The detailed findings, using these figures are listed here and are from Test No. F31141.

1. Prior to editing, the outer gimbal standard deviation was 16.8 and the inner gimbal was 4.75 microradians; acceptable.
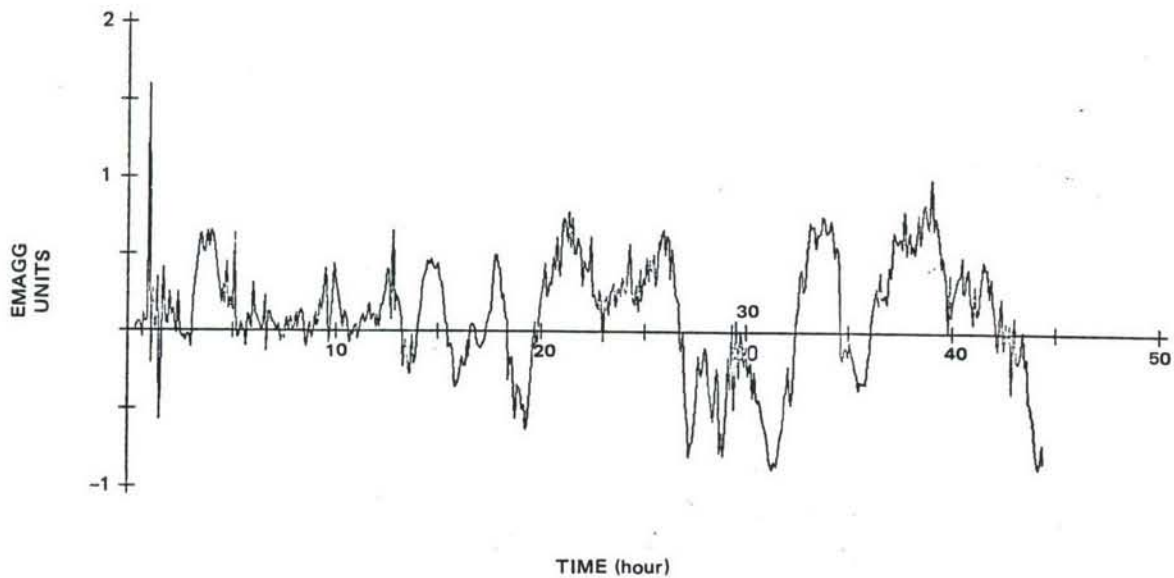
Figure 6-1. Residual error in magnitude of gravity;
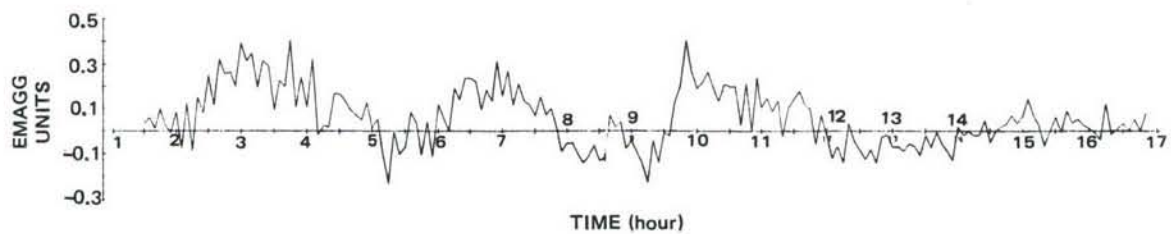Test No. C2051CA.

Figure 6-2. Residual error in magnitude of gravity;
Test No. H31131 (Carousel).

2. After editing outer was 16.2 and the inner gimbal was 4.75 microrad; acceptable.

3. Before and after range standard deviations were .0159 and .0081 meters, respectively, both corresponding to single-shot values; acceptable.

4. The range data shows 10-15 cm spikes which can be filtered out by data editing for the near term and may be eventually filtered out with hardware changes, if deemed appropriate.

6.5 APTS ACCEPTANCE TEST RESULTS

6.5.1 IMU DRIFT TEST

The results of this test demonstrated that the real-time navigation mission could be achieved in that the accumulated drift would be less than the required 7 arcsec in the two level channels and less than approx. 60 arcsec in azimuth over the simulated mission duration. These results are acceptable as shown by Fig. 6-3 which contains the IMU gimbal angles in radians. Note that the angles shown represent the sum of the outer case motion and the actual stable member drift. Other plots, not included here, show the individual terms of drift.

6.5.2 NAVIGATION TEST

Acceptance test no. F31061 demonstrated that the largest real-time navigation error was approx. 25 meters which compares well with the requirement of 60 meters (Fig.6-4). As the figure shows, the unaided navigation error grows until the tracking updates are received and than a reset occurs. The error growth of the IMU attitude was less than the required seven arcsec. over the entire test. This demonstrates the ability of the system to meet the real-time navigation requirements; i.e., to have the accuracy to be able to point the Tracker close enough to the retro such that they can be acquired. The actual drift value was approx. five arcsec. per axis. Note that there was a large nav. error at approx. 838 sec. after the start of nav. This result was a procedural error rather than a real system problem. The error involved commanding an incorrect retro identification while the Tracker was still locked onto the target. The largest error not caused by a procedural error was approx. 18 meters, compared with the 60 meters allowed.

The recorded data were processed using a 15-state postflight filter and a 9-state smoother. The residual position error
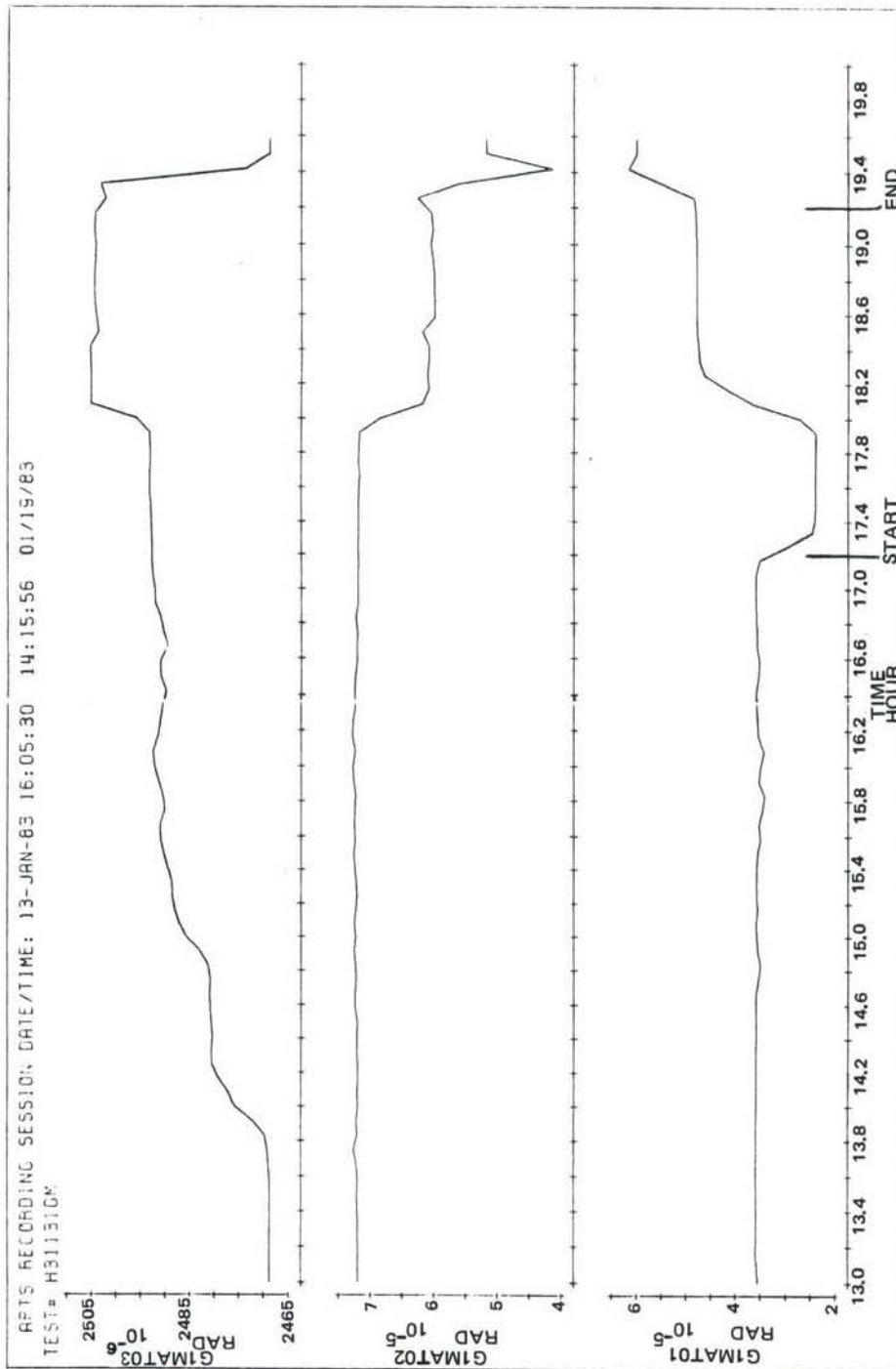
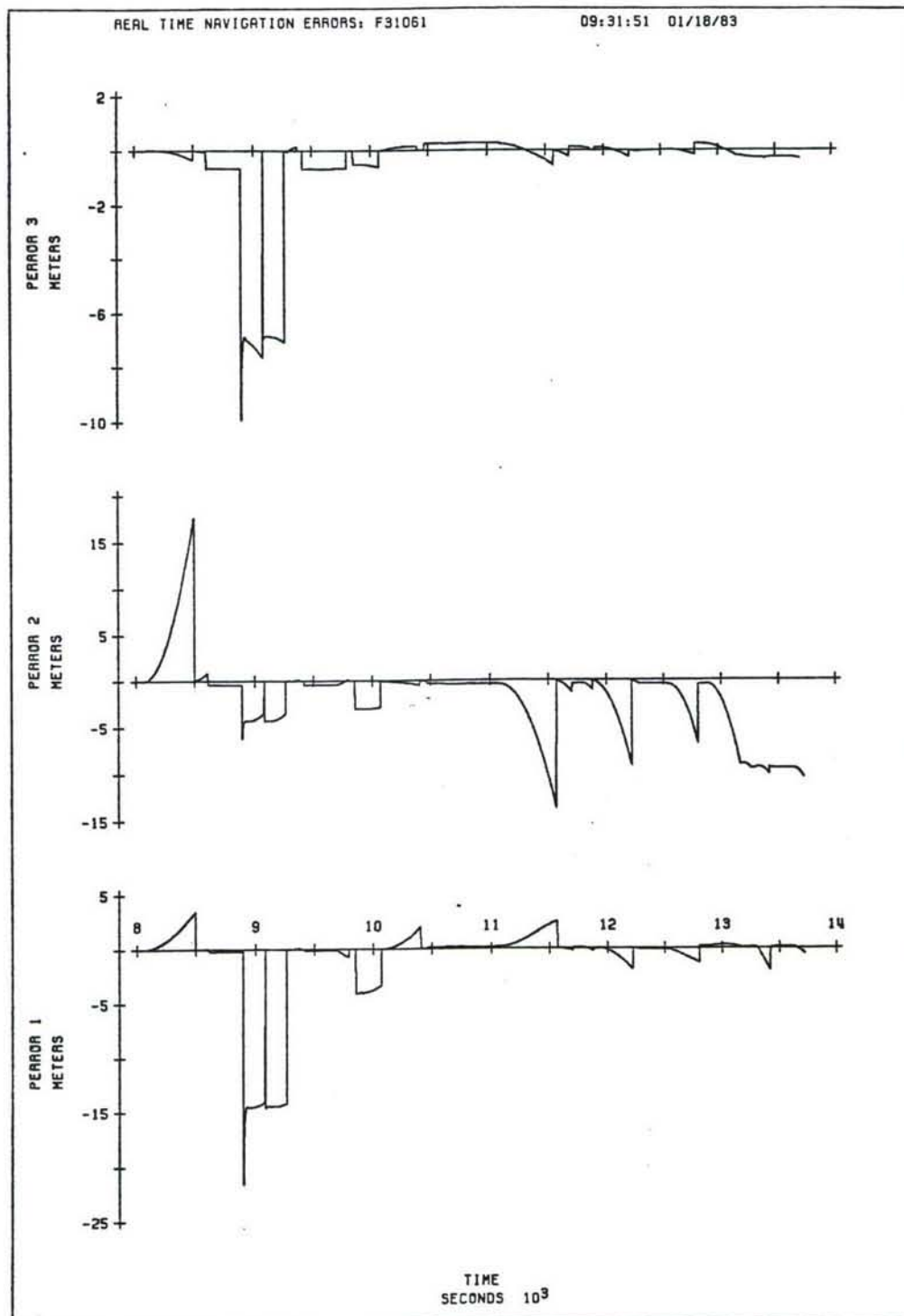Figure 6-3. IMU acceptance drift test.

Figure 6-4. Real-time position errors, North, East, Down;
Test No. F31061.

after smoothing was less than the .6 meter, horizontal and .15 meter vertical permitted by the APTS requirements. This was the result for 100 per cent of the time as compared with the 90 per cent required. The peak residual position error was .36 meter and the peak residual velocity error was .005 m/s. Fig. 6-5 shows the real-time velocity error. Figures 6-6 and 6-7 are the filtered position and velocity errors respectively. All of these data are considered acceptable. Fig. 6-8 illustrates the residual IMU drift after the Carousel, also acceptable.

Acceptance test F31141 also produced acceptable results. The largest real-time error not caused by an erroneous retro lock-on was 62 meters at time 1050 sec as shown by Fig. 6-9. The relatively large value of this error was caused by the extensive time between updates, approx. 550 seconds. The large real-time error at 1900 sec. was caused by lock-on to an interior reflective surface of the laboratory rather than a retro.

The platform drift was acceptable, also, as shown by the postflight filter the largest value was 6.7 arcseconds. Again in this test the postflight filter indicated horizontal and vertical component errors were less than .6 meters horizontal and .15 meters vertical, 100 per cent of the time. Peak residual position error was .48 meters and velocity error was .003 m/s. maximum. Both of the maxima occurred at 400 seconds; i.e., before Tracker data became available. Fig. 6-10 shows the velocity errors, real-time, and Figs. 6-11, 6-12 show the postflight filter results on position and velocity. Figure 6-13 is a set of plots showing the platform angle drifts, all of which are acceptable.
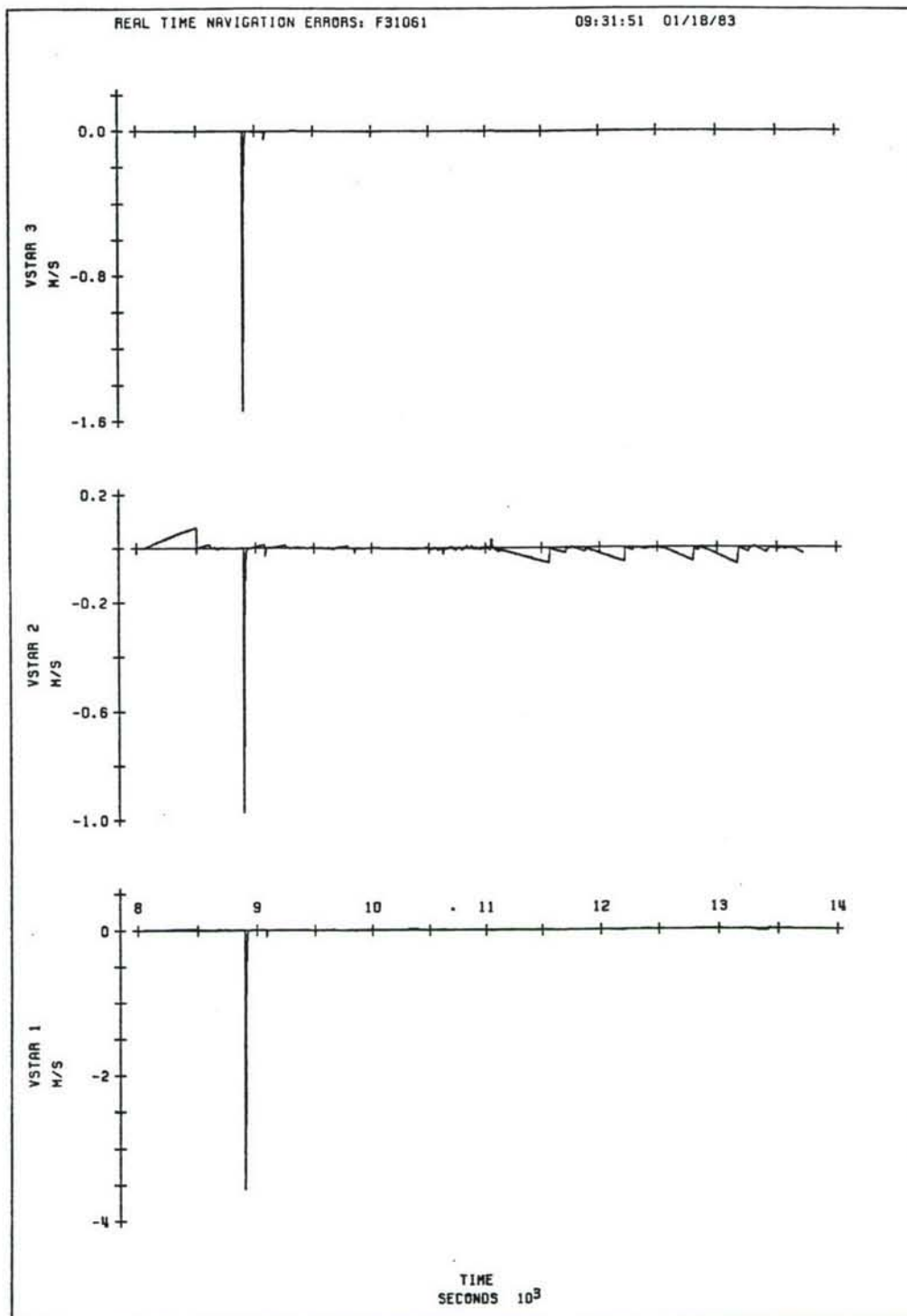
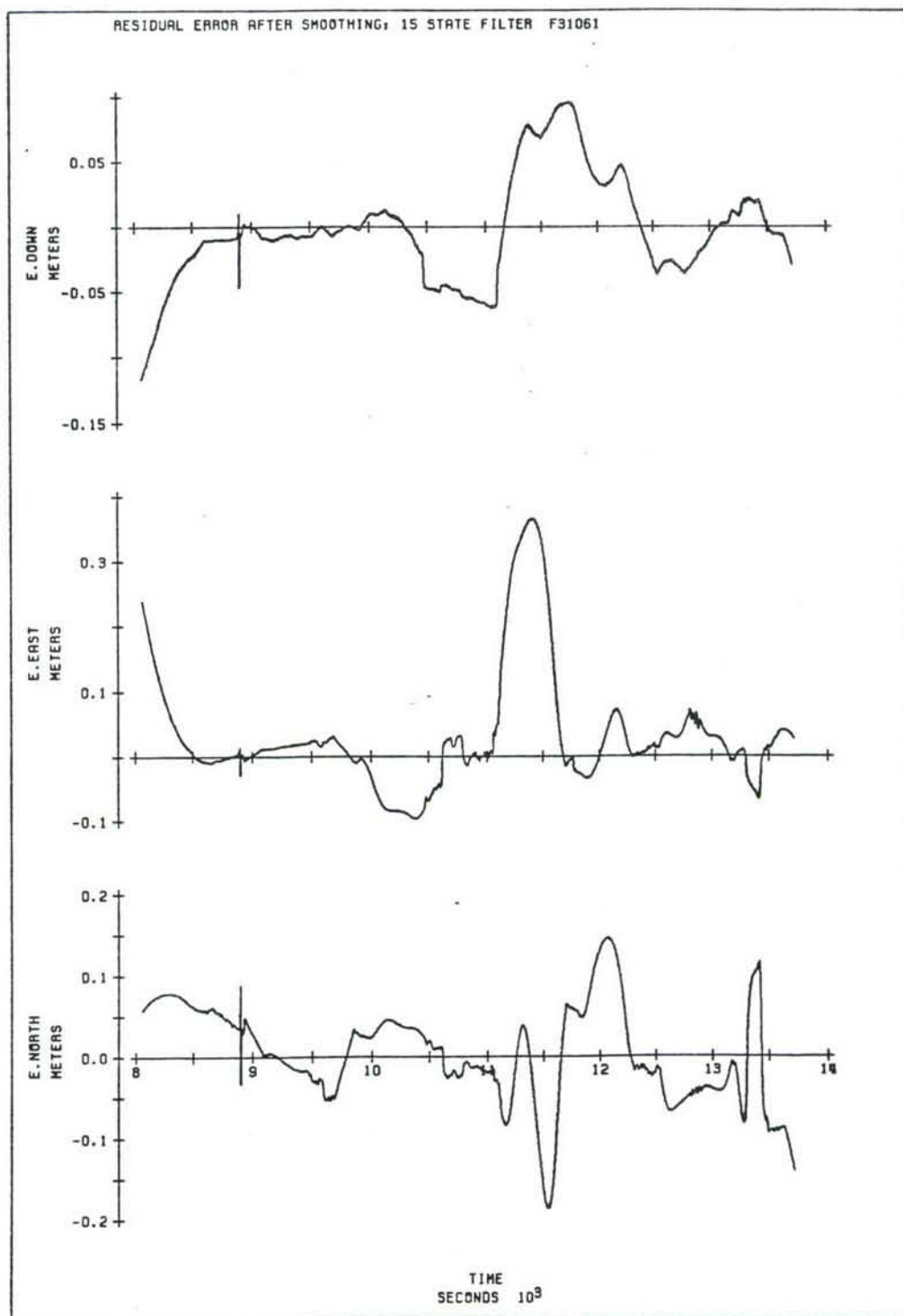Figure 6-5.   Real-time velocity errors, North, East, Down;
Test No. F31061.

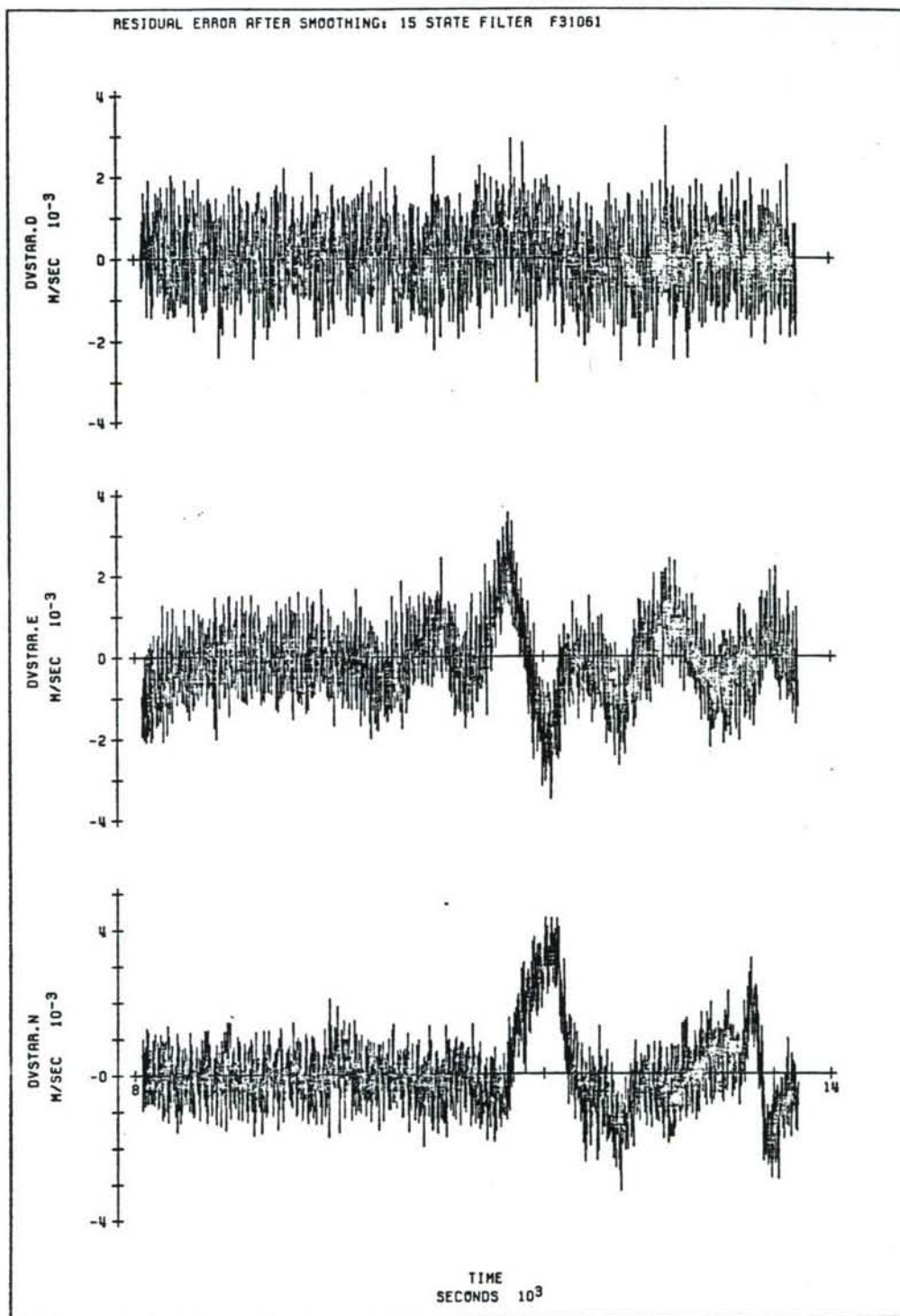Figure 6-6. Filtered and smoothed position errors;
Test No. F31061.

Figure 6-7. Filtered and smoothed velocity errors;
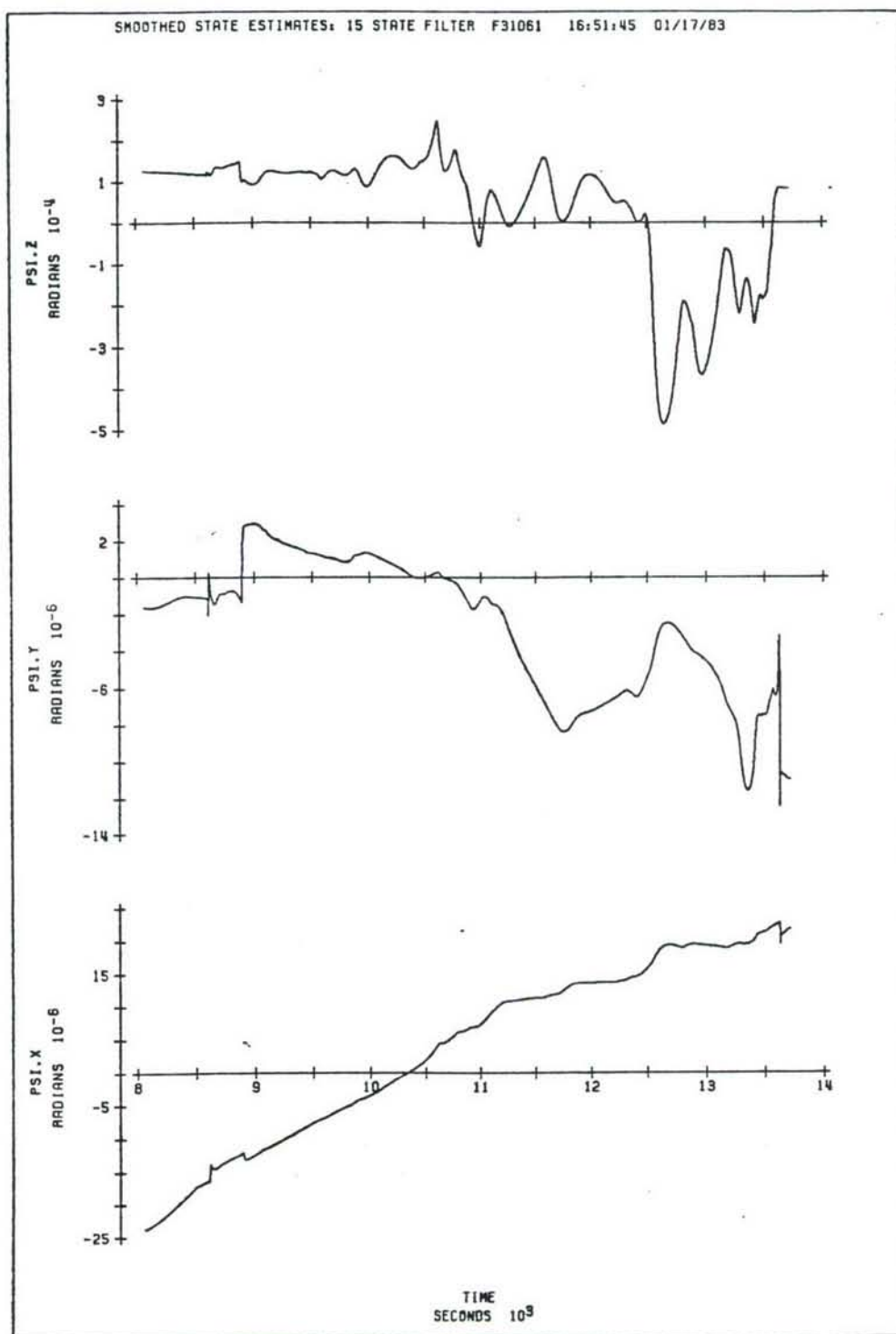Test No. F31061.

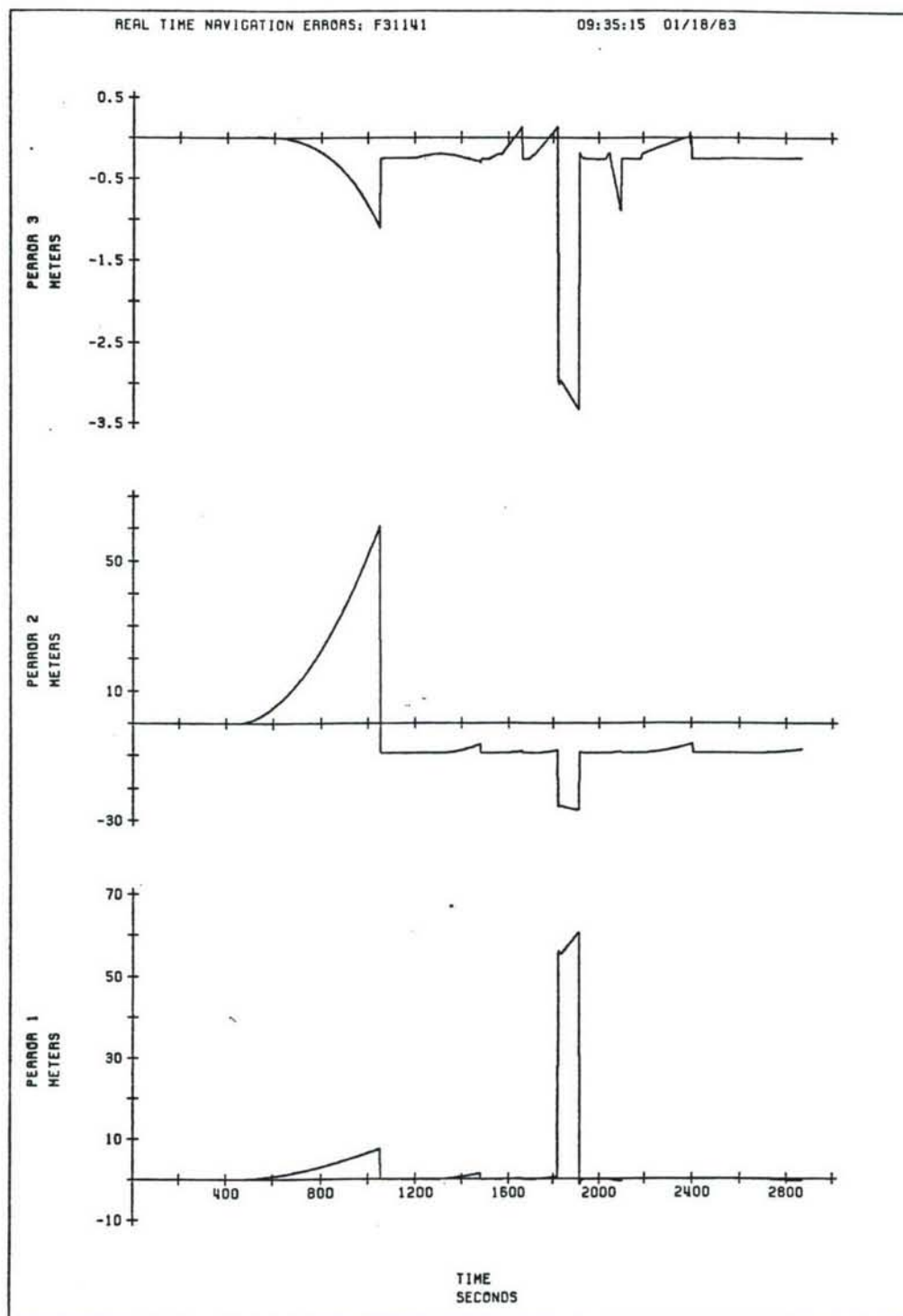Figure 6-8.   IMU misalignment angles, filtered and smoothed;
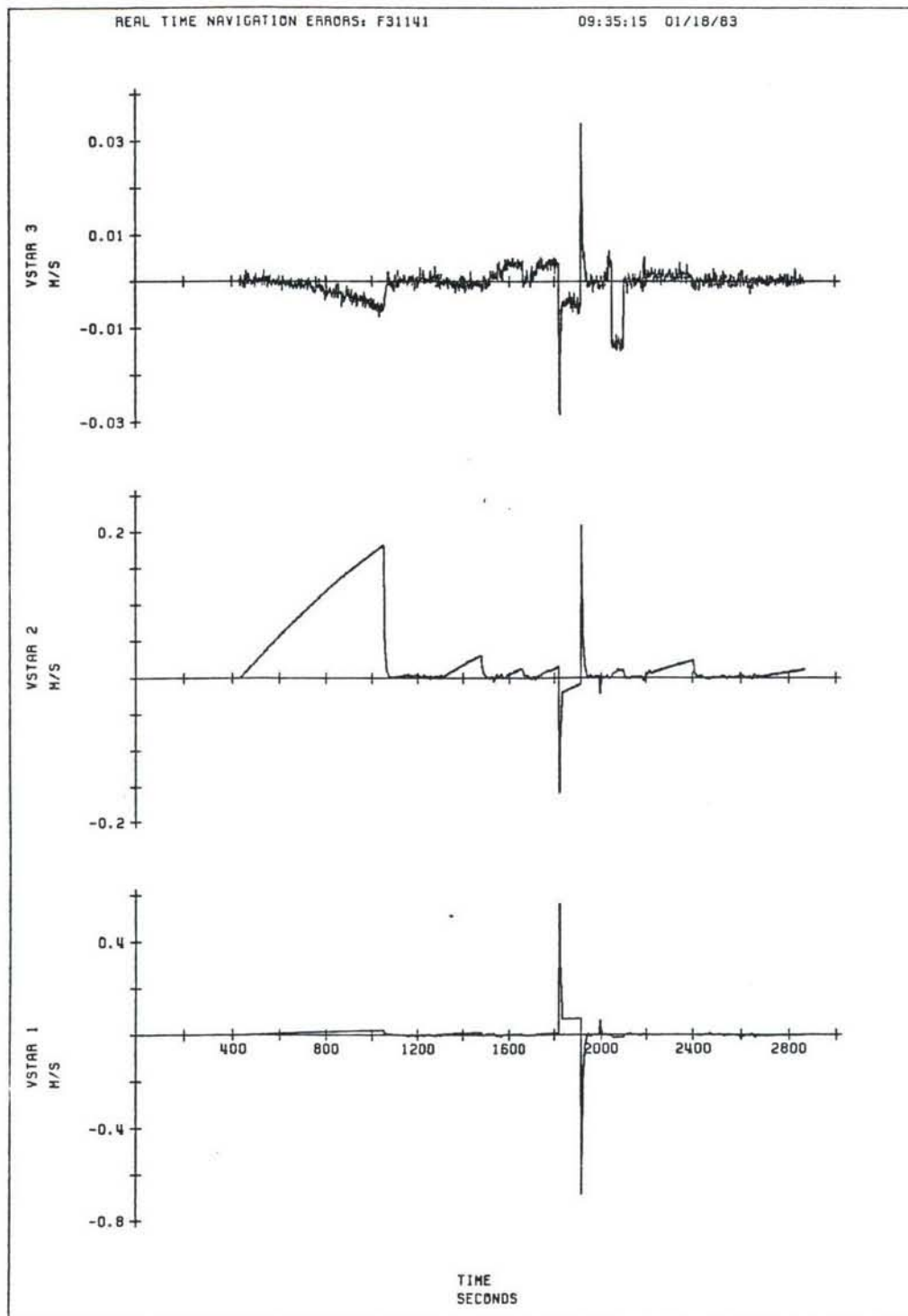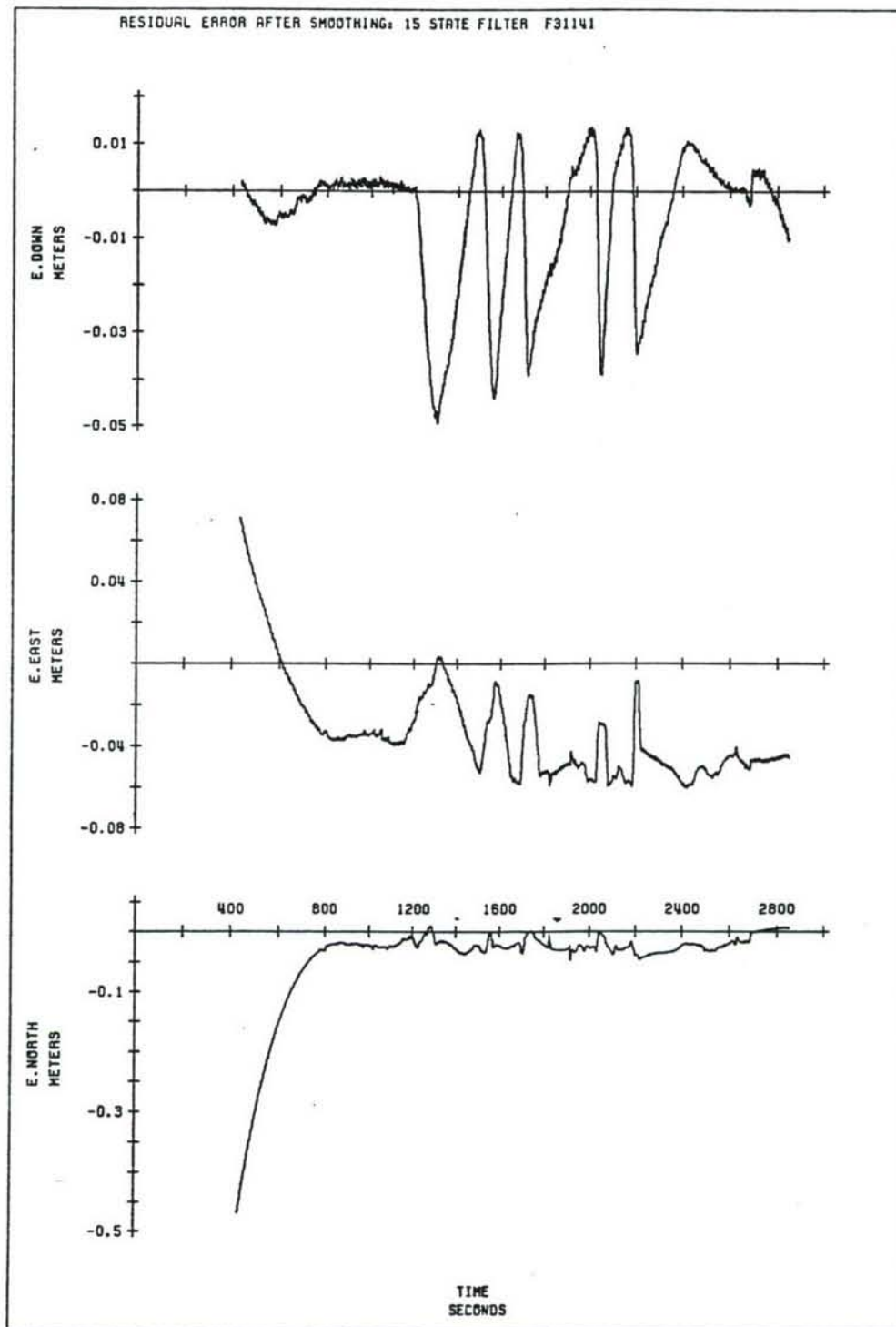Test No. F31061.

REAL TIME NAVIGATION ERRORS: F31141   09:35:15 01/18/83

Figure 6-9. Real-time position errors, Test No. F31141.

Figure 6-10.   Real-time velocity errors, Test No. F31141.

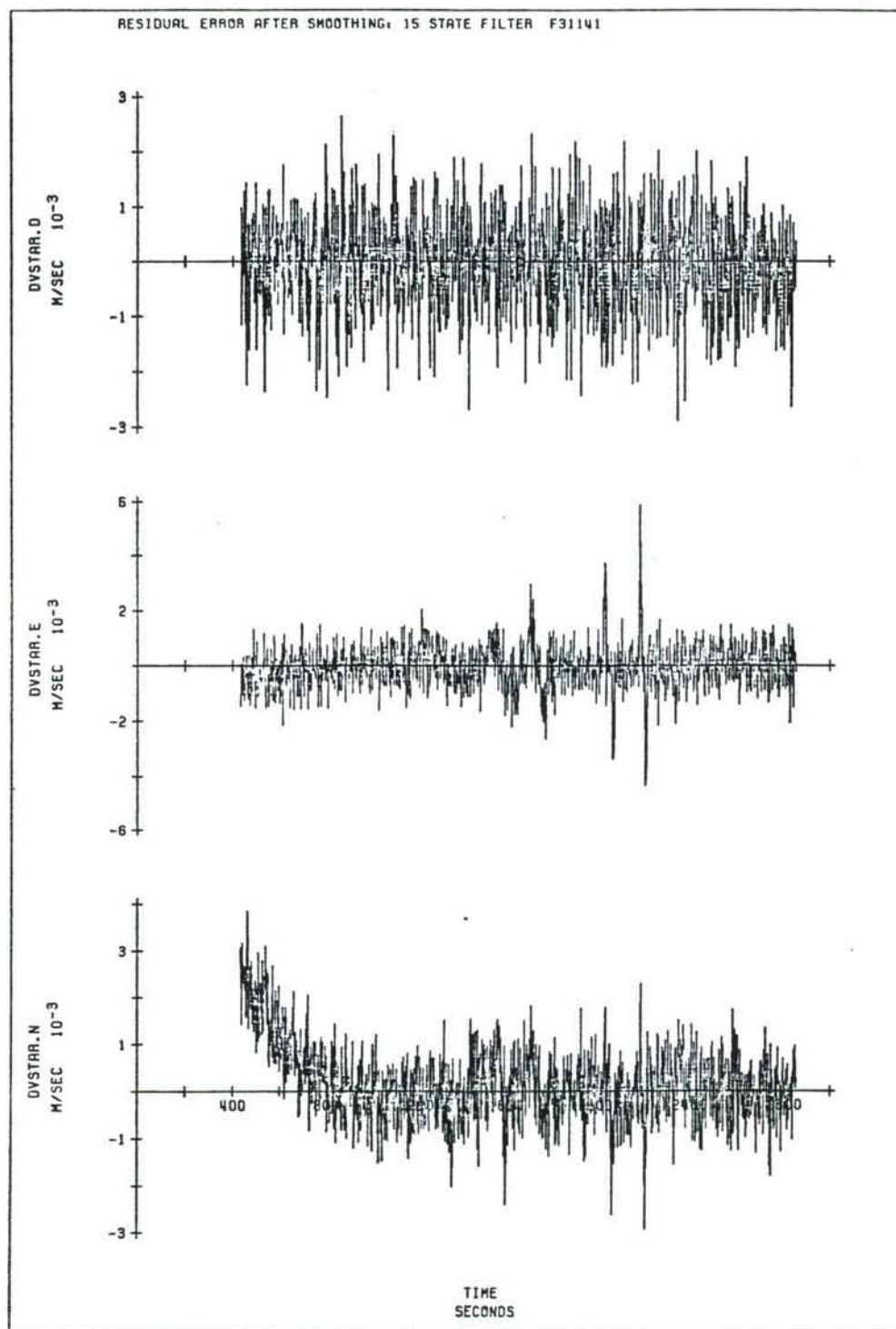Figure 6-11. Filtered and smoothed position errors;
Test No. F31141.

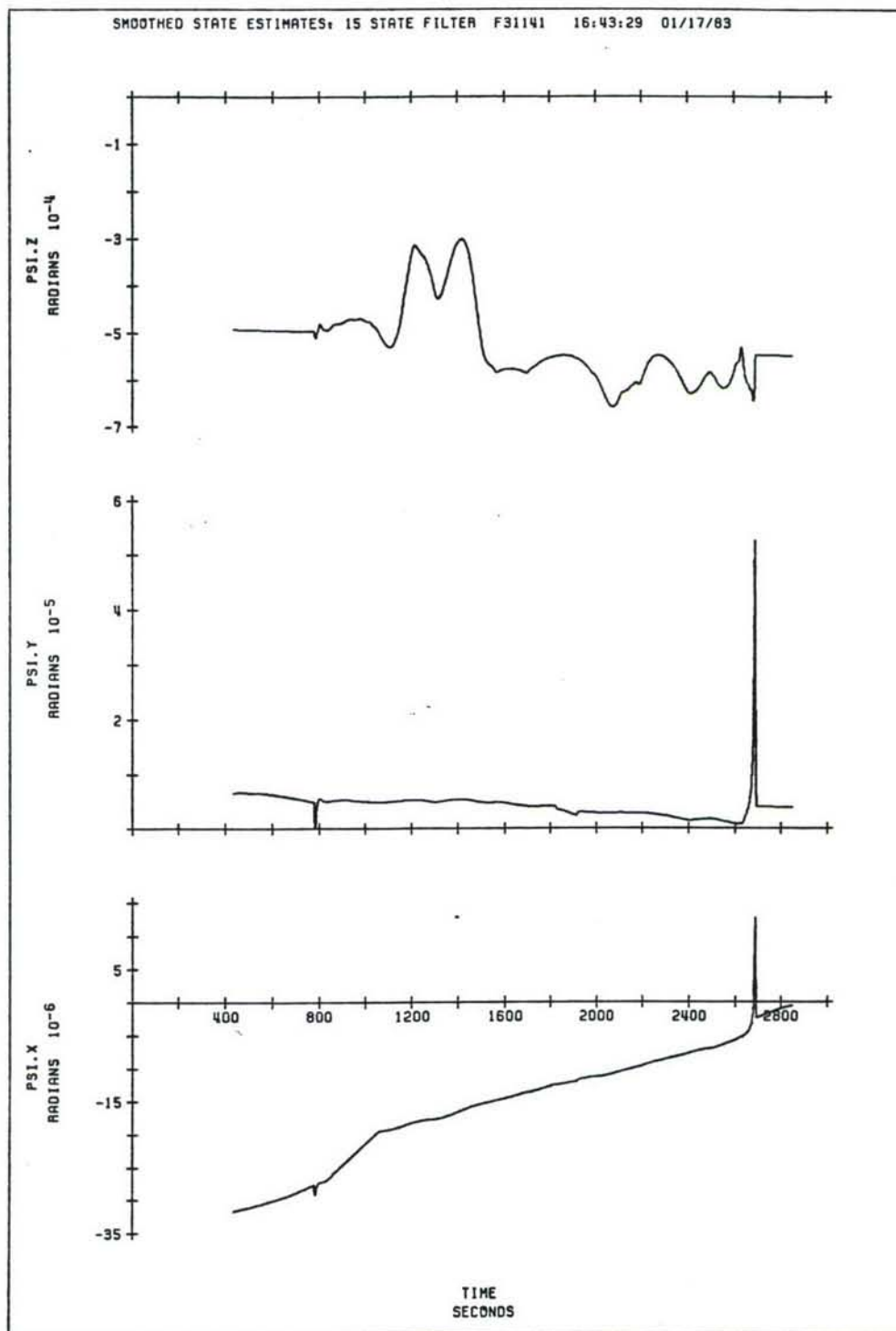Figure 6-12. Filtered and smoothed velocity errors;
Test No. F31141.

Figure 6-13. IMU misalignment angles, filtered and smoothed; Test No. F31141.

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ACCEPTANCE TEST PROCEDURE

FOR THE

AERIAL PROFILING OF TERRAIN SYSTEM

REV -

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1. SCOPE AND OBJECTIVES

1.1 Scope

This document specifies and describes, at an engineering level, the laboratory procedures for acceptance testing of the Aerial Profiling of Terrain System (APTS) in order to verify functions and performance.

1.2 Objectives

The APTS laboratory acceptance tests shall verify functions and performance as follows:

(1) Verify all IMU/Tracker/Software functional modes necessary to conduct IMU Calibration and Alignment (C&A), Standby mode for flight, unaided inertial navigation, Tracker-aided navigation, IMU C&A post-processing, and navigation data post-processing.

(2) Verify IMU/Tracker/Software performance accuracy necessary to complete an APTS mission in accordance with the acceleration error, platform misalignment, gyro drift and navigation error specified in Applicable Document No. 1.

The other APTS elements which are separately tested are the Video subsystem which will be verified using the flight procedure of Applicable Document No. 2 and the Laser Profiler which was tested under Applicable Document No. 3. The Retro arrays will be tested in conjunction with preflight testing of APTS at Hanscom Field.

2. APPLICABLE DOCUMENTS

(1) Charles Stark Draper Laboratory APTS Program Review IV for U. S. Geological Survey 28, 29 September 1982, Presentation by J. A. Soltz Vol. 1 (see Tables 4-1 & 4-2 herein).

(2) CSDL Document, Flight Test Procedure for the Aerial Profiling of Terrain Video Subsystem, Rev 1, October 1982.

(3) CSDL Document R-1521, <u>Aerial Profiling of Terrain System</u>
    <u>Transitional Phase Final Report on Test of the Inertial</u>
    <u>Navigation, Laser Tracker and Laser Profiler Subsystems</u>,
    December 15, 1981.

(4) CSDL Document No. R-1451, <u>Aerial Profiling of Terrain</u>
    <u>System, Phase V Fabrication, Assembly and Testing</u>, July 1982.

3. TEST SYSTEM AND EQUIPMENT USED

3.1 Test System

The hardware elements of the APTS which shall be tested under
this procedure are shown in Figure 3-1 and are individually identified
with an asterisk. The software elements of the system which shall be
tested are the Real-Time C&A program, System Modes Routines, C&A Post-
Processor, Flight Data Editor, and Flight Data Post-Processor. Detailed
descriptions of the hardware and software are provided by Applicable
Document No. 4.

3.2 Equipment Used

The IMU/Tracker shall be mounted onto the Goerz Table in the
normal operating orientation for the acceptance test. A set of interior-
laboratory and exterior-laboratory retroreflectors shall be provided
for the aided inertial navigation portion of the test (see Figures 3-2
and 3-3). Preselected retros from this set shall be acquired and
tracked with the Laser Tracker.

4. IMU/TRACKER/SOFTWARE PERFORMANCE REQUIREMENTS

4.1 Accuracy of Performance

4.1.1 Calibration and Alignment

Verify by means of the acceptance test and post-
processor that the acceleration error, platform misalign-
ments and gyro drift uncertainty are within the maximum
values given by Table 4-1 below.
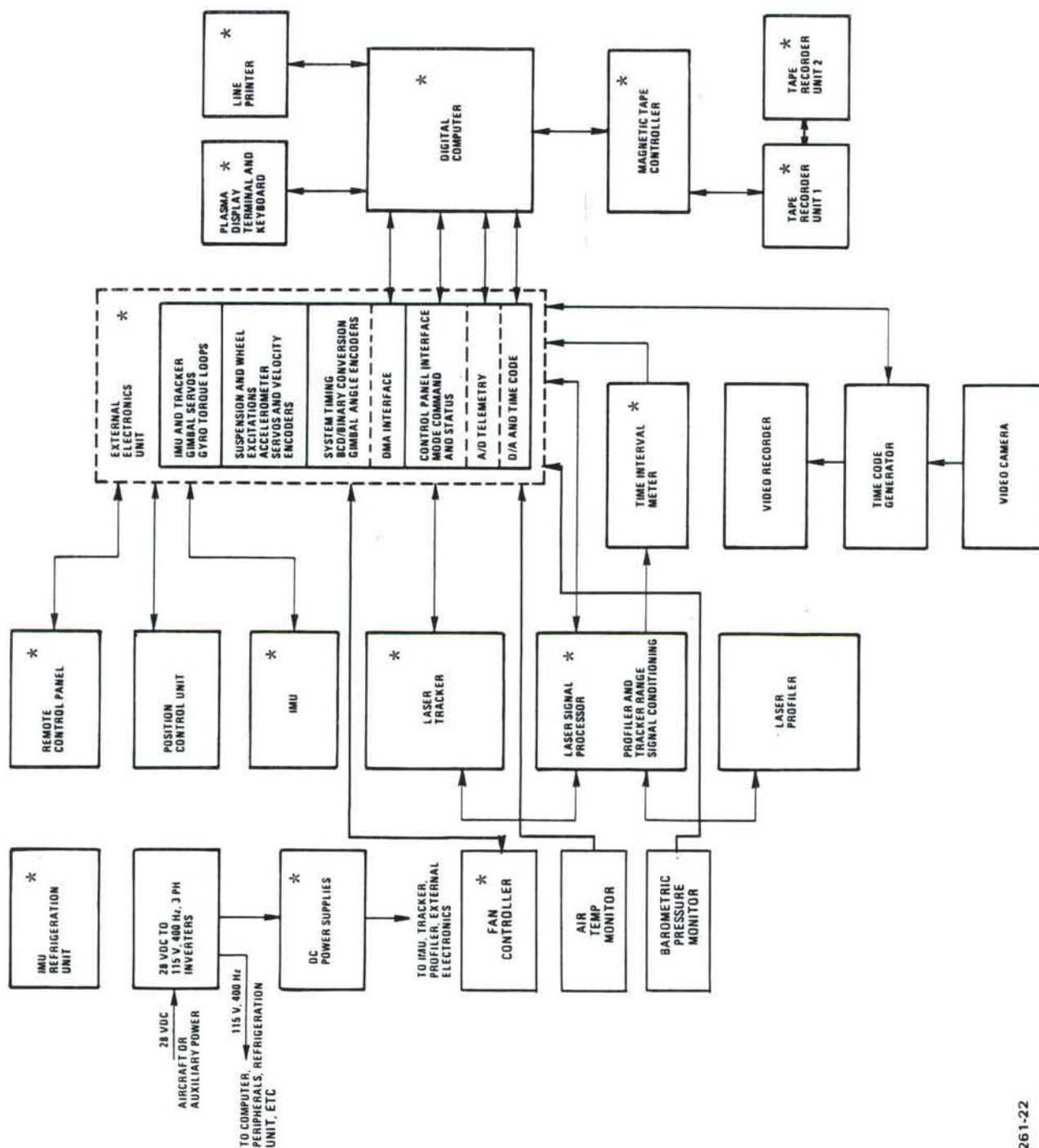
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Figure 3-1. Aerial Profiling of Terrain System (APTS)
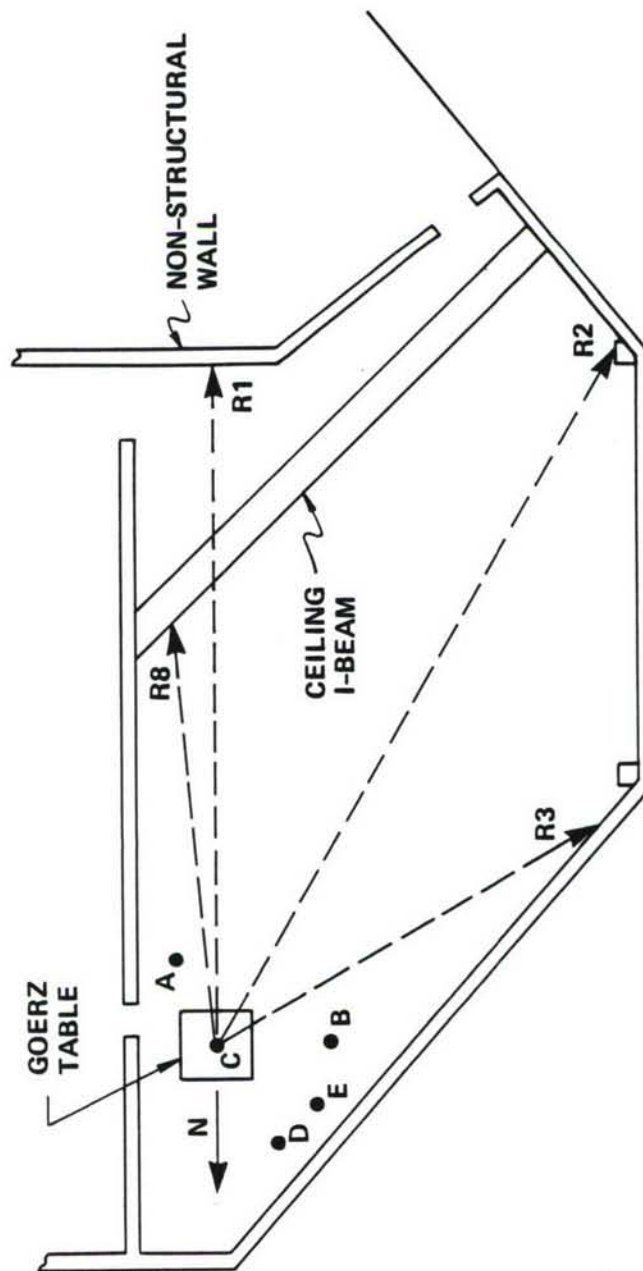Block Diagram

8009A261-22

Figure 3-2. Interior-Lab Retros

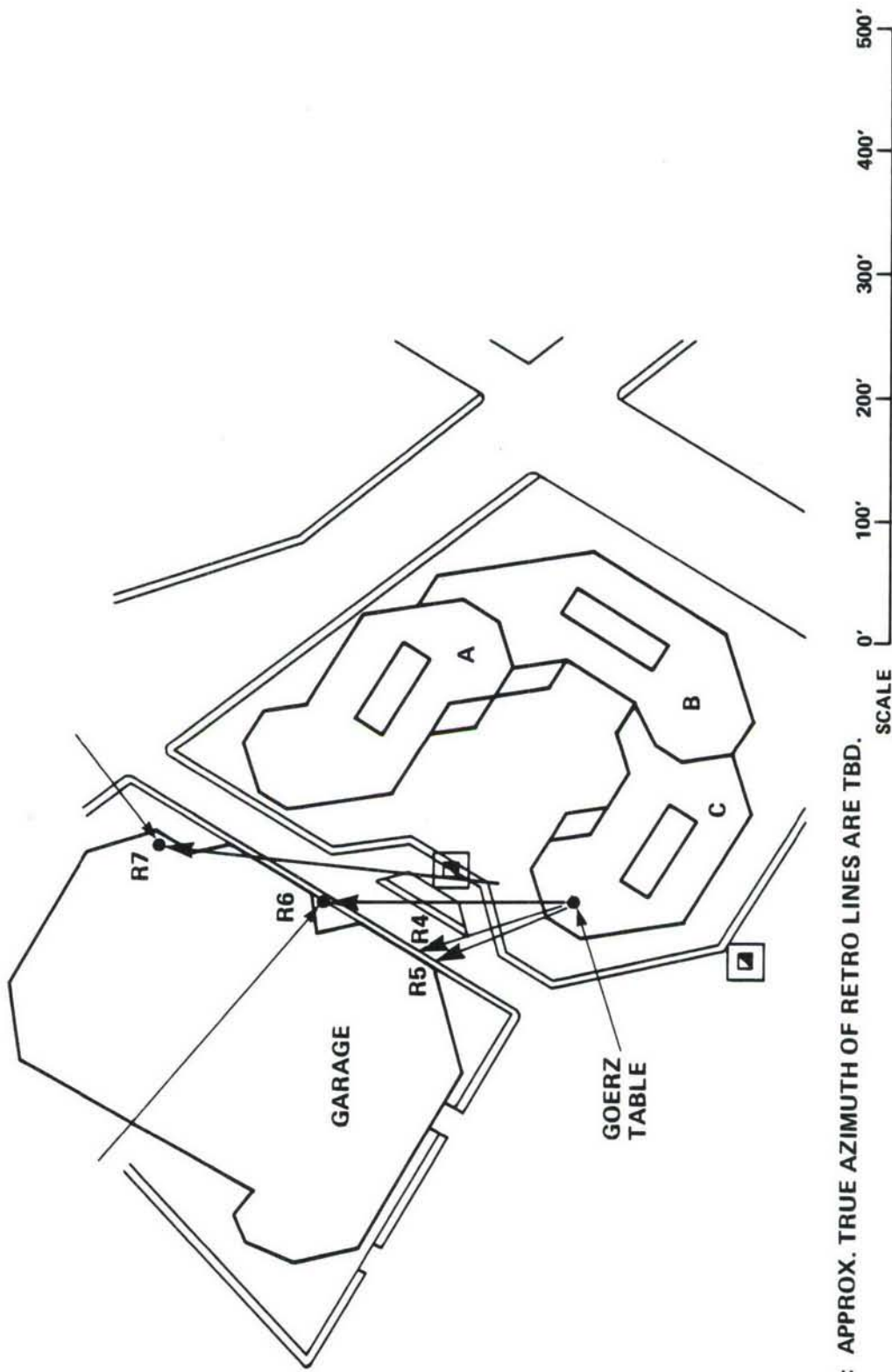NOTE: APPROX. TRUE AZIMUTH OF RETRO LINES ARE TBD.

SCALE

Figure 3-3. Exterior-Lab Retros

8207B245 2

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4.1.2   Navigation

Verify by means of the acceptance test and post-processor that the real-time and post-processed navigation performance will be within the maximum values given by Table 4-2 below.

Table 4-1.   Accuracy Requirements During a 2½ Hour Mission

PARAMETER	VALUE	EFFECT
ACCELERATION ERROR	34 μg	ALL THREE COORDINATES
PLATFORM MISALIGNMENT	7 sec	HORIZONTAL ONLY
GYRO DRIFT	52 mmeru	HORIZONTAL ONLY

Table 4-2.   Summary of Navigation Error Requirements

	REAL-TIME	POST-PROCESS
HORIZONTAL	60 m	60 cm*
VERTICAL	60 m	15 cm*

* 90% of the time

5.0   ACCEPTANCE TEST PROCEDURE

5.1   General Approach

The acceptance test shall be comprised of four segments: Moding and Data Initialization, C&A, Standby, and Navigation. The first segment shall verify the capability to mode and initialize the software/hardware preparatory to an APTS mission. Secondly, the C&A shall measure and verify the IMU parameters. Thirdly, the Standby Mode shall hold the IMU stable member with the fixed gyro torque values derived from the end of the C&A such that residual acceleration misalignment and gyro drift values can be measured. Finally, the Navigation segment shall

verify unaided and tracker-aided navigation.

5.2 <u>Test Procedure</u>

Figure 5-1 illustrates the four test segments. Record magnetic
tape data for the three segments beginning with C&A.

5.2.1 Moding and Initialization

1. Mode the APTS from servos off through to the stabiliza-
   tion mode.

2. Load the data initialization tape and print the initial
   values.

3. Torque the IMU to 0, 0, 0 (outer, middle, inner) gimbal
   angles.

4. Mode the IMU into the C&A.

5.2.2 IMU Calibration and Alignment

1. Conduct the 53-hr. C&A test.

2. At the conclusion of C&A, disable the gyro torque at
   the final values.

5.2.3 Standby Mode

1. Mode the APTS to the Standby Mode.

2. Maintain Standby for two hours.

3. Provide an alignment reset at the conclusion of the
   standby segment.

5.2.4 Navigation

1. Enter the Navigation Mode.

2. Rotate the IMU on the Goerz Table in ±180 degree se-
   quences in accordance with Table 5-1 below.

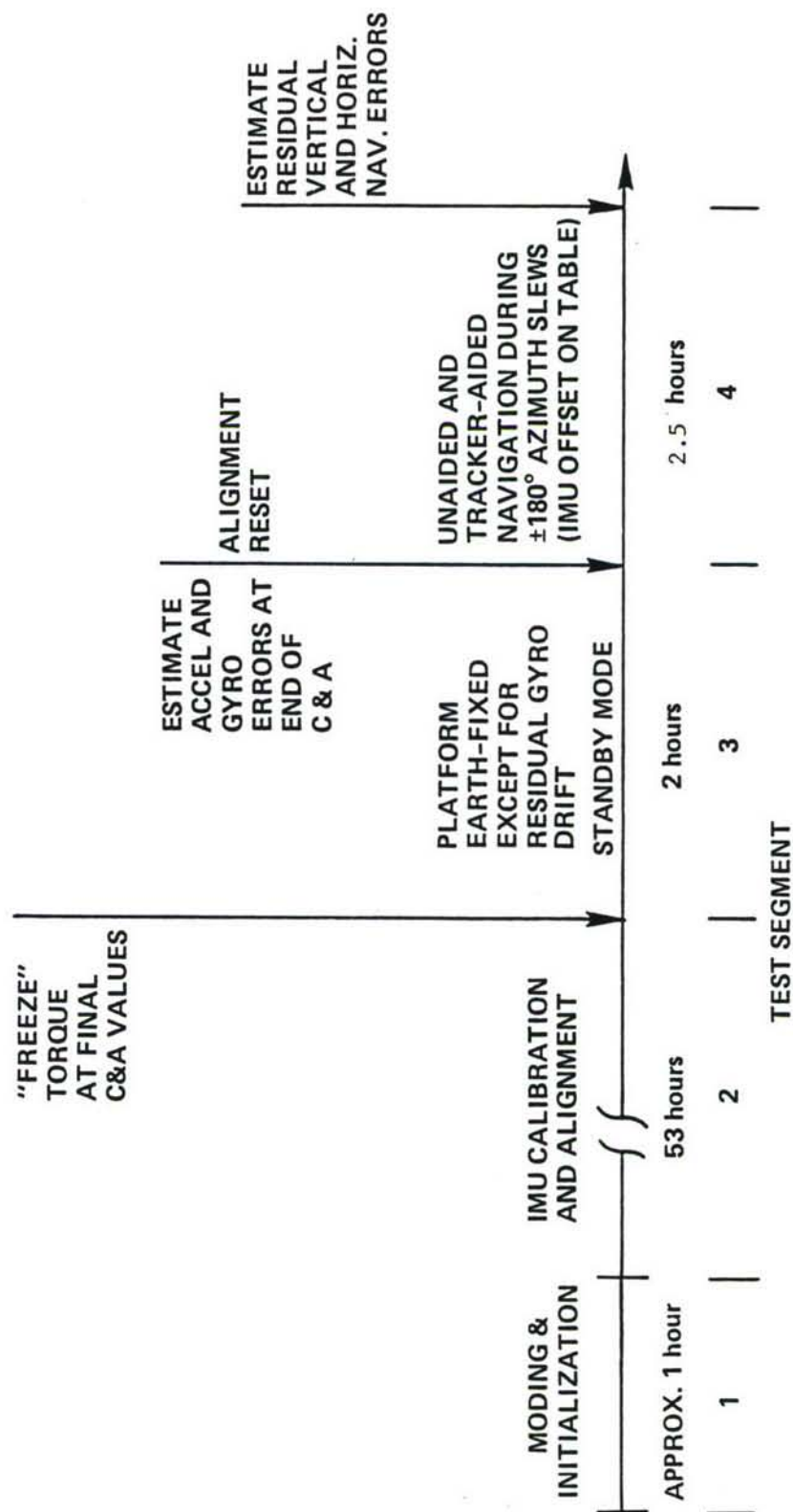Figure 5-1. APTS IMU/TRACKER/SOFTWARE
PERFORMANCE ACCEPTANCE TEST

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Table 5-1

Algorithm for APTS
Navigation Acceptance Test

Cycle No.	Rotation, Goerz Table Angle (deg)	Goerz * Table Rate (deg/s)	Elapsed Time, (s) (approx)	Pauses (s)	Retros Tracked No.	Remarks
1.1	+180	1	180		1	Start from zero degs. Track one retro every 200 s (approx). Pauses allow cable adjustments.
1.2	pause	0		104		
1.3	-180	1	180		2	
1.4	pause	0		104		
1.5	+180	1	180		3	
1.6	pause	0		104		
1.7	-180	1	180		4	
1.8	pause	0		104		
1.9	+180	1	180		5	
1.10	pause	0		104		
1.11	-180	1	180		6	
1.12	pause	0		104		
Totals	1080		1080	624	6	
2.1–2.12	1080	2	540	624	3	Repeat 1.1–1.12 at 2 deg/s
3.1–3.12	1080	3	360	624	2	
4.1–4.12	1080	4	270	624	1	
5.1–5.12	1080	5	216	624	1	
6.1–6.12	1080	6	180	624	1	
7.1–7.12	1080	6	180	624	1	
Repeat Steps 1.1 – 1.12	1080		1080	624		Measure performance at 2.5 hrs elapsed time
Grand Totals	8640	–	3906	4992		

* Reduce Goerz Table rates if necessary for retro acquisition.

3. Acquire and track a retro approximately every 200 seconds. Provide known alignment resets to the navigation function to permit retro acquisitions at close ranges.

5.2.5 Verification of Data

1. Post process all C&A, Standby and Navigation Data.

2. Verify APTS functions and performance in accordance with the data sheets in Table 5-2 below.

3. Retain all data for the APTS Phase VI Final Report.

Table 5-2. Verification of APTS Functions and Performance

Test Procedure Paragraph	Function or Performance	Acceptable (A) Not Acceptable (NA)	Notes
4.1.1	IMU C&A		Ref. Table 3-1
4.1.2	Navigation		Ref. Table 3-2
5.2.1	Moding & Initialization		List any moding or display discrepancies throughout the acceptance test.

APTS R&QA - Laboratory Systems Testing

Throughout the laboratory testing phase for APTS, the Reliability and Quality Assurance (R&QA) Department provided support in several essential areas. The objective of this support effort was to assure that all of the APTS equipment, while being used and subsequent to changes, would remain as an operational entity.

It was decided during the early stages of the laboratory testing to always have R&QA engineering in attendance during disassembly and reassembly of the IMU. Visually examined were hardware, wiring, connectors, subassemblies, and all other visible system aspects. This close attention has resulted in defective fan replacements, hardware replacements and a connector repair. The total elapsed time of both disassembly and assembly proved to be lessened where R&QA participated directly.

An essential part of R&QA support activity is the maintenance and calibration of all APTS test equipment including oscilloscopes, meters, recorders, etc. The calibration assures that test equipment and other instruments used for measurements are within their accuracy specifications. These calibrations occur at periodic intervals against standards that are traceable to the National Bureau of Standards (NBS).

One important area of R&QA support is the activity of failure analysis. When parts failed they were removed and delivered to the R&QA laboratory for analysis. The analysis pursued the cause of failure to the point at which it was determined whether the part failed of its own accord or of induced causes. This rapid diagnostic information is a valuable troubleshooting aid and the resulting cost and test schedule impacts were lessened accordingly. Corrective action efforts were also added thus precluding repetitive-type failures.

At the conclusion of the laboratory testing, selected subsystems were subjected to a vigorous visual examination for workmanship. The objective being to verify that visual aspects of workmanship appear to be free of potential problems that could effect field readiness or reliability of the system. The examinations were planned to obtain as much insight into the condition of the equipment without introduction of problems or wasting time on unnecessary examinations.

Certain purchased subsystems were not subjected to an internal examination since their history and nature lead us to conclude that they were acceptable as-is. We did subject these subsystems to a visual examination of their outer features for possible signs of damage.

The TV camera and its associated video recorder were both exempted from visual examination. These instruments are designed to be rugged so as to be capable of withstanding field use under relatively harsh conditions.

Each subsystem, including purchased items which could possess environmental limiting aspects underwent a complete, as practical, visual examination.

All IMU & EEU assemblies were visually examined for workmanship, cleanliness, and especially for the presence of wire clippage and other pieces of metal that could move about under vibration.

The visual examination revealed a few damaged and worn parts; however, most of the problems found were with loose wires and electrical interconnections. The somewhat marginal wire-wrap and solder joints were touched-up and all loose wires were secured with adequate stress relief.

Fault logs were established for each subsystem of APTS. The fault logs will provide a valuable historical record of each subsystem's reliability experience and configuration. These logs will also provide information necessary for future maintenance planning.